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Tensile Creep of Boron/Epoxy and Boron/Epoxy-Reinforced 7075-T6 Aluminum Alloy

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Tensile Creep of Boron/Epoxy and Boron/Epoxy-Reinforced 7075-T6 Aluminum Alloy

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Daniel J. Chwirut

Tensile creep tests were performed on twelve specimens of 0° unidirectional boron/epoxy and on twenty-four specimens of 7075-T6 aluminum alloy reinforced with 0° unidirectional boron/epoxy. An analytical procedure for predicting the creep properties of composite-reinforced metals is presented. Agreement between calculated and experimental creep curves varies with test temperature. These discrepancies between experiment and analysis are probably not due to an error in the analysis itself, but rather to uncertainty in the residual stresses in the specimens.

Key words: Aluminum alloy; boron/epoxy; composite materials; creep; elastic follow-up technique; sandwich specimen.

1. INTRODUCTION

Within the past few years, advanced composites have made dramatic progress, going from a laboratory-availability status to a production commitment in some components of the next generation of advanced aircraft systems [1].[1] There seem to be two different approaches toward the application of advanced composites in the United States at present. One approach advocates the use of composites for complete components whenever practical, whereas the other approach advocates the use of composites only to reinforce metals. The investigation reported herein was undertaken to help answer one of the questions about composites when applied using the latter approach: What are the long-term strength properties of metals when reinforced with an organic-matrix composite, specifically a structural aluminum alloy reinforced with boron/epoxy?

The resistance of boron filaments to creep at temperatures below 1200 °F (650 °C) has been reported to be excellent [2]. At these temperatures no measurable creep was observed at stresses up to the fracture stress.

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[1]Figures in brackets indicate the literature references on page 18.

Experimental data on creep of 0° unidirectional organic-matrix composites are scarce. The data that have been reported are somewhat conflicting. Shockley et al. [3] report that a creep strain of about 1400×10^{-6} was measured after 4 hours at 106,000 lbf/in^2 (7.3×10^8 N/m^2) and 270 °F (132 °C) in 0° unidirectional boron/epoxy. Lou and Schapery [4] claim that negligible creep is found in unidirectional glass fiber-reinforced epoxy when loaded parallel to the fibers. Most work on creep of organic-matrix composites reported in the literature involves either crossplied specimens or off-axis loading of unidirectional specimens, indicating that this is where most of the concern lies. In a 0° unidirectional boron/epoxy specimen with 50 percent by volume of fibers, the fibers support approximately 98 percent of the total load on the specimen. Since the fibers do not creep, little or no creep would be expected in the composite.

Metal-matrix composites, however, specifically boron/aluminum, have been found to undergo creep and rupture at temperatures below 930 °F (500 °C) when loaded along the axis of the fibers in tension [5-6] and in three-point bending [7]. Ruptures occurred in some tests at stresses less than 50 percent of the tensile strength of the composite. Reference 7 indicates that a considerable increase in rupture life can be achieved by increasing the fiber volume fraction from 40 to 60 percent.

The creep resistance of a boron-filament composite thus seems to be directly related to the percentage of the total load on the composite carried by the filaments as well as the creep properties of the matrix. It is logical to assume, therefore, that creep would also be possible in light-alloy structures reinforced with organic-matrix composites, since the parent metal still carries a significant part of the total load.

The investigation reported here was undertaken to experimentally evaluate the creep properties of 7075-T6 aluminum alloy reinforced with 0° unidirectional boron/epoxy, and to determine if these data can be predicted analytically from creep data for each of the components. This work was performed at the National Bureau of Standards under the sponsorship and with the financial assistance of the National Aeronautics and Space Administration, Langley Research Center.

2. SYMBOLS

The units used for physical quantities in this paper are given in both the U. S. Customary Units and in the International System of Units (SI). Conversion factors pertinent to the present investigation are presented in Appendix A.

Appendix B contains a glossary of terms whose meaning may not be widely known or whose usage in this paper is different or more restrictive than the generally accepted definition.

A crossectional area

E modulus of elasticity (when referring to the modulus of boron/epoxy in this report E denotes the modulus along the axis of the fibers, commonly called E_{11})

P load

ΔP an incremental change in load

S stress

t time

Δt an incremental change in time

α coefficient of linear thermal expansion

ε strain

$\Delta\varepsilon$ an incremental change in strain

subscripts

a aluminum alloy

b boron/epoxy

r residual

t total

superscripts

0 initial, i.e., at the start of the test

3. TEST SPECIMENS

3.1. Boron/Epoxy Specimens

The composite specimens tested during this investigation were unidirectional boron/epoxy, with the filaments alined along the axis of loading. The specimen geometry is shown in figure 1(A). The boron/epoxy material was supplied by the 3M Company[2] in continuous tape form with

[2]The identification of the suppliers of materials used in this program is for information purposes only and is not intended to indicate endorsement by the National Bureau of Standards, nor does it imply that the material was necessarily the best available.

nominally 212 filaments per inch (83 filaments per cm) of tape width. The boron filaments were nominally 0.004 in (0.1 mm) in diameter and pre-impregnated with PR-279 epoxy resin. Each ply of boron/epoxy had a glass scrim backing, 0.001 inch (0.03 mm) thick.

The specimens were cured with the platen-press technique using pressures and temperatures recommended by the manufacturer. Five samples of material were taken from each plate of composite laminate and mounted in a cast epoxy metallurgical mount. A photomicrograph at 100 x magnification was taken of each sample, and the volume fraction of the sample was determined from the photomicrograph by determining what fraction of the total intersections of a grid overlay fell on filaments. The filament volume fraction for each plate was taken as the average of the fractions of the five samples. All of the specimens tested in this investigation were taken from laminated plates having filament volume fractions between 47 and 54 percent.

3.2. Aluminum Alloy Specimens

Aluminum alloy specimens were cut from a single sheet of 0.032-in (0.8-mm) thick 7075-T6 aluminum alloy. All specimens were cut so that the longitudinal axis of the specimen was in the direction of rolling of the sheet. The specimen geometry was the standard flat tensile specimen (ASTM Designation E8-69, Fig. 6), with a reduced section approximately 7 in (18 cm) long (see fig. 1(B)). Unless otherwise indicated, all specimens were preconditioned by a thermal treatment of one hour at 325 °F (163 °C) and five hours at 350 °F (177 °C) prior to testing. This simulated the thermal treatment experienced by the aluminum alloy during the co-cure processing of the sandwich specimens which is discussed below.

3.3. Sandwich Specimens

Sandwich specimens were tested which consisted of 2, 4, 6, 8, or 12 plies of boron/epoxy bonded between two sheets of 0.032-in (0.8-mm) thick 7075-T6 aluminum alloy. The specimen geometry is shown in figure 1(C). Two methods were used to fabricate these specimens; a two-step process in which the boron/epoxy laminate was cured first and then bonded to the aluminum alloy, and a co-curing process in which the boron/epoxy laminate was cured and bonded to the aluminum alloy in one process.

a. Two-Step Process

The initial sandwich specimens were fabricated by bonding precured boron/epoxy laminates between two sheets of aluminum alloy using Armstrong's C-4 epoxy and activator W in a 1:1 ratio and cured at 200 °F (93 °C). The advantages of using this technique are good dimensional control of the composite, low residual stresses due to fabrication, and control of composite volume fractions. The disadvantage is that the epoxy adhesive is ineffective at temperatures above 200 °F (93 °C), as the specimens tended to delaminate when tested at these temperatures. Attempts using a higher temperature rated epoxy adhesive were unsuccessful.

b. Co-curing Process

The majority of the sandwich specimens tested in this investigation were fabricated by curing the composite and bonding it to the aluminum alloy in the same operation. Good adhesion between composite and aluminum alloy was achieved for temperatures up to 300 °F (149 °C). The disadvantages of this technique are the lack of control of the volume fractions of the composite, because no excess epoxy is bled from the prepreg during the cure, and the introduction of significant residual stresses in the components due to the different coefficients of thermal expansion of the composite and aluminum alloy. Volume fractions for these specimens were not measured, but based on specimen thicknesses the composite was judged to be approximately 40 percent filaments and 60 percent epoxy.

4. TEST EQUIPMENT

The experimental apparatus used in this investigation is shown in figure 2.

4.1. Creep Testing Machines

The test program was conducted in two deadweight creep testing machines. Both machines have lever arms with ratios of 10:1. Specimen alinement was achieved by using knife edges in the load train of one machine and spherical seats in the other machine.

Prior to initiation of testing, both machines were calibrated in accordance with ASTM Designation E4-64, Standard Methods of Verification of Testing Machines. Errors in applied loads were less than one percent. Bending strains induced in the specimen were measured using an aluminum alloy specimen instrumented with four strain gages located to measure bending in two planes. The maximum deviation of any single strain reading from the average of the four readings was less than two percent of the average.

4.2. Strain Measurement Equipment

Two systems were used to measure and record creep strains--a high sensitivity system used in tests on boron/epoxy and sandwich specimens, and a low sensitivity system used in tests on aluminum alloy specimens. Both systems employed extension rods to allow the sensing element to remain outside the test furnaces.

a. High Sensitivity System

Figure 3 shows a sandwich specimen with extension rods and extensometer sensing elements attached. The sensing elements are two dc linearly variable differential transformers (LVDT's) which measured the extension over a 4-in (10-cm) gage length in the center of the specimen. The outputs from the LVDT's were amplified and recorded continuously on a dual-channel, voltage-time recorder. The strain in the specimen was taken as the average of the two strain measurements. This system was calibrated using a micrometer extensometer comparator. Strains of 4×10^{-6} could be resolved, and uncertainties in strain measurement were less than five percent of the measured value or 8×10^{-6}, whichever is greater.

b. Low Sensitivity System

Figure 4 shows an aluminum alloy specimen with extension rods and a commercial LVDT extensometer attached. This extensometer measured the the extension of a 3-in (8-cm) gage length in the center of the specimen. The output from the extensometer was amplified and recorded continuously on a time-based recorder. This system did not average the strain on the two sides of the specimen, but it was considered adequate because bending strains measured during testing machine calibration were small. This system was calibrated using an extensometer comparator and gage blocks. Strains of 13×10^{-6} could be resolved, and uncertainties in strain measurement were less than five percent of the measured value or 26×10^{-6}, whichever is greater.

4.3. Heating Systems

The test furnaces were each composed of a cylindrical section of 0.5-in (1-cm) thick asbestos-cement pipe approximately 10 in (25 cm) in inside diameter and 7 in (18 cm) in length. These were designed so that the gage section in the center of the specimen could be evenly heated while the grips could be outside of the furnace. This was done in an effort to eliminate failures in the grip. The top and bottom of the cylinder were covered with three layers of 0.75-in (2-cm) thick fiberglass insulation. Heat was supplied by four 1000-watt quartz lamps, wired in pairs, with separate power control for each pair. Temperature was measured with three or four thermocouples taped to the specimen in

the gage section. Temperature was controlled and recorded by a time-proportioning, recording controller.

5. TEST PROCEDURE

The same procedures were followed for tests on all three types of specimens. The specimen was cleaned with acetone to remove any dirt and oil. The extensometer extension rods were attached at the appropriate gage points, and thermocouples were taped to the specimen. The specimen was mounted in the testing machine and final adjustments were made to the strain measurement system.

The specimen was heated to the test temperature in approximately 20 min. Adjustments were made to the temperature controller to reduce the temperature variations to an acceptable level. A gradient of 3 °F (2 °C) or less along the gage length of the specimen and a variation of ±2 °F (1 °C) at the center of the specimen were considered acceptable. The specimen was then maintained at this condition for 30 minutes prior to application of load. Loading was accomplished smoothly and rapidly by lowering the weights onto the lever arms using a hand crank on one machine and a screw jack on the other.

Extension and temperature were continuously recorded for the duration of each test. When extensions approached the limit of the recorders, the extensometers were reset. Tests were usually terminated after 100 hours if no rupture had occurred.

6. TESTS AND EXPERIMENTAL RESULTS

6.1. Static Tests

Tensile tests at four temperatures were performed on boron/epoxy specimens and aluminum alloy specimens to determine values for the elastic moduli to be used in the computations. The procedure outlined in ASTM Designation E231-69, Static Determination of Young's Modulus of Metals at Low and Elevated Temperatures, was followed, except that resistance strain gages were used instead of extensometers. The results of these tests are given in table 1. The measured moduli for both materials were approximately constant at temperatures up to 300 °F (149 °C), and for the computations the following values were used for all temperatures:

boron/epoxy: $E = 32 \times 10^6$ lbf/in^2 (22×10^{10} N/m^2)

aluminum alloy: $E = 9.6 \times 10^6$ lbf/in^2 (6.6×10^{10} N/m^2)

6.2. Residual Strain in Sandwich Specimens

The longitudinal residual strains in the aluminum alloy of sandwich specimens, resulting from fabrication, were measured at room temperature on one specimen fabricated by each process.[3] This was done by bonding a resistance strain gage to the aluminum alloy and measuring the strain relieved when the specimen was carefully delaminated. For the co-cured specimen the residual strain was 2270×10^{-6} in tension. For the specimen fabricated by the two-step process the residual strain was 30×10^{-6} in tension.

6.3. Creep Tests

a. Creep of Boron/Epoxy Specimens

A total of twelve creep tests on boron/epoxy specimens was attempted at four temperatures. Four of the specimens failed immediately upon application of the test load, which was less than the nominal maximum strength of the material as measured in the static tests. Five other specimens failed after sustaining the test load for a period of time. Four of these failed in the grip and one in the gage section. Limited creep data were obtained for these specimens, although the failures were not considered valid stress-rupture failures for the material because they occurred at or near the grip. Three specimens survived 120 hours without failure. The test conditions and results for the twelve tests are given in table 2.

b. Creep of Aluminum Alloy Specimens

Sixteen tensile creep tests on 7075-T6 aluminum alloy specimens were performed at four temperatures. The test conditions and results are given in table 3. Except as noted these specimens had been preconditioned as mentioned in section 3.2. The families of creep curves for the four temperatures are given in figures 5 through 8.

c. Creep of Sandwich Specimens

Tensile creep tests on nineteen sandwich specimens with four plies of boron/epoxy between two sheets of 7075-T6 aluminum alloy were performed at four temperatures. The test conditions and results are given in table 4. The families of creep curves for the four temperatures are

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[3]Measurements made on additional specimens are discussed later.

given in figures 9 through 12. Note that some tests are replicates of others in which the specimen failed prematurely in the grip. The nominal stresses in the aluminum alloy and the boron/epoxy were calculated by assuming that the total test load on each specimen was distributed between the two components so that the axial elastic strain in both were equal.

Tensile creep tests on five sandwich specimens with 2, 6, 8, 8, and 12 plies of boron/epoxy were performed at 300 °F (149 °C) and one initial stress level to determine the effect of composite-to-metal volume ratio. Test conditions and results for these tests are given in table 5. The creep curves for these specimens are given in figure 13. Figure 14 summarizes the effect of composite-to-metal volume ratio on the creep behavior and rupture life of the sandwich specimens. Note that specimen BA-37 seems to be an anomaly, and the results of this test were not considered in constructing the curves in figure 14.

7. ANALYTICAL PREDICTION OF CREEP CURVES

From earlier work done at this laboratory Mordfin [8] presented an analytical procedure for predicting creep curves for creep deflections of non-uniform beams. Experimental verification of this analysis [9] showed good correlation between experimental and analytical values. This analysis used the "elastic follow-up technique" developed by Popov for stress redistribution in non-uniform structures [10]. A similar analysis was used by Hayashi to predict creep of unidirectional fibrous composites [11]. An analysis similar to these is applied to creep of sandwich specimens in this investigation, using Hayashi's assumption that the longitudinal strains in all components are equal.

7.1. Theory

The maximum creep strain in boron/epoxy measured in the investigation was less than 10 percent of the elastic strain in the specimen. This seems to verify that no significant creep occurs in 0° unidirectional boron/epoxy at temperatures up to 300 °F (149 °C). However, it was hypothesized that effective creep could occur in composite-reinforced metals by the following procedure:

a. At time t = 0, the aluminum alloy is under a stress S_a^o and the boron/epoxy is under a stress S_b^o.

b. The aluminum alloy tends to creep but, since the strain in the aluminum alloy cannot exceed the strain in the boron/epoxy, the aluminum alloy undergoes stress relaxation instead.

c. Since the total load on the specimen is constant, the stress in the boron/epoxy increases as the aluminum alloy relaxes, thus causing increased elastic strain which is measured and called "creep" in the sandwich specimen.

d. Rupture occurs when enough stress redistribution has occurred so that the stress in the boron/epoxy exceeds the tensile strength of the material.

Both the strain-hardening and time-hardening rules for accumulation of creep streain the the aluminum alloy were used. The assumption of the strain-hardening rule is that the instantaneous creep rate is a function of the instantaneous stress and the amount of creep strain that has taken place. The assumption of the time-hardening rule is that the instantaneous creep rate is a function of the instantaneous stress and the time the material has been creeping.

7.2. Analytical Procedure

At time $t = 0$, the aluminum alloy supports a load P_a^o and is at a stress S_a^o, where $S_a^o = \frac{P_a^o}{A_a} + S_r$. The boron/epoxy supports a load P_b^o.

The total load on the specimen is $P_t = P_a^o + P_b^o$, and P_t remains constant for the duration of the test. P_a^o and P_b^o are calculated assuming that the total load P_t is distributed between the aluminum alloy and the boron/epoxy so that the axial elastic strain in both are the same.

During an initial time increment, Δt, the aluminum alloy at stress S_a^o tends to creep an amount ε_a, determined from the experimental creep curves for the aluminum alloy specimens. It is assumed that creep in the boron/epoxy is negligible. Since the strain in the aluminum alloy is constrained to remain equal to the strain in the boron/epoxy, the total load P_t is redistributed by an amount ΔP so that at the end of the time increment Δt

$$P_a = P_a^o - \Delta P$$

and

$$P_b = P_b^o + \Delta P.$$

Assuming an elastic follow-up, this load redistribution causes a strain change

$$\Delta\varepsilon_a = \frac{-\Delta P}{E_a A_a}$$

and

$$\Delta\varepsilon_b = \frac{\Delta P}{E_b A_b} \tag{1}$$

where the absolute sum of these changes equals ε_a (see fig. 15). That is,

$$-\Delta\varepsilon_a + \Delta\varepsilon_b = \varepsilon_a . \tag{2}$$

Substituting eq (1) into eq (2)

$$\frac{\Delta P}{E_a A_a} + \frac{\Delta P}{E_b A_b} = \varepsilon_a$$

or

$$\Delta P = \frac{\varepsilon_a}{\dfrac{1}{E_a A_a} + \dfrac{1}{E_b A_b}} . \tag{3}$$

The creep in the sandwich specimen during time increment Δt is $\Delta\varepsilon_b$, which, from eq (1) and (3), is

$$\Delta\varepsilon_b = \frac{\varepsilon_a}{1 + \dfrac{E_b A_b}{E_a A_a}} . \tag{4}$$

The aluminum alloy is now at a stress

$$S_a = \frac{P_a}{A_a} + S_r$$

Another time increment is taken, and the procedure is repeated under the new conditions.

7.3. Illustration

As an illustration, consider Specimen BA-16, tested at 225 °F (107 °C). The crossectional areas of the boron/epoxy and aluminum were:

$$A_b = 0.0114 \text{ in}^2 \ (7.35 \times 10^{-6} \text{ m}^2)$$

$$A_a = 0.0315 \text{ in}^2 \ (2.03 \times 10^{-5} \text{ m}^2).$$

Substituting these values and the values of elastic moduli into eq (3) and (4) gives

$$\Delta P = \frac{\varepsilon_a}{6.05 \times 10^{-6}} \text{ lbf or } \Delta P = \frac{\varepsilon_a}{1.36 \times 10^{-6}} \text{ N} \qquad (3)$$

and

$$\Delta\varepsilon_b = \frac{\varepsilon_a}{2.2} \ . \qquad (4)$$

The total test load, P_t, was 2750 lbf (12,232 N).

The values of P_a^o, P_b^o, and S_a were calculated as follows:

$$\text{elastic strain} = \varepsilon = \frac{P_a^o}{E_a A_a} = \frac{P_b^o}{E_b A_b} \text{ and } P_t = P_a^o + P_b^o$$

so

$$P_b^o = P_a^o \frac{E_b A_b}{E_a A_a} \ .$$

Therefore,

$$P_t = P_a^o \left(1 + \frac{E_b A_b}{E_a A_a}\right) = 2.2 \ P_a^o$$

or

$$P_a^o = \frac{P_t}{2.2} = 1260 \text{ lbf } (5604 \text{ N})$$

and

$$P_b^o = P_t - P_a = 1490 \text{ lbf } (6628 \text{ N})$$

The value of residual stress in the aluminum alloy, S_r , was estimated assuming a linear variation from zero at 350 °F (149 °C) where the composite-to-aluminum bond was cured, to the measured value at 75 °F (24 °C). At 225 °F (107 °C), this value is 9700 lbf/in^2 (6.69×10^7 N/m^2). The initial stress in the aluminum alloy, S_a^o , is 49700 lbf/in^2 (3.43×10^8 N/m^2).

Taking, as a first time increment, $\Delta t = 0.01$ h, $\varepsilon_a = 400 \times 10^{-6}$ (interpolated from fig. 7). Therefore, from eq (3) and (4), $\Delta P = 66$ lbf (294 N) and $\Delta\varepsilon_b = 181 \times 10^{-6}$. The first point on the analytical creep curve is thus $t = 0.01$ h, $\varepsilon = 181 \times 10^{-6}$. The new conditions at $t = 0.01$ h are $P_a = 1194$ lbf (5311 N), $S_a = 47{,}600$ lbf/in^2 (3.28×10^8 N/m^2), and $P_b = 1556$ lbf (6921 N).

During the next time increment, $\Delta t = 0.04$ h, the aluminum alloy is considered to remain at 47, 600 lbf/in^2 (3.28×10^8 N/m^2). The strain-hardening rule predicts that the strain rate in the aluminum alloy is a function of stress and previous creep strain, so ε_a is taken from the curve for 47,600 lbf/in^2 (3.28×10^8 N/m^2), starting at a creep strain of 400×10^{-6}, over a time increment of 0.04 h. Using this method, $\varepsilon_a = 80 \times 10^{-6}$, $\Delta P = 13$ lbf (58 N), and $\Delta\varepsilon_b = 36 \times 10^{-6}$. The second point on the strain-hardening creep curve is then $t = \Sigma\Delta t = 0.05$ h, $\varepsilon = \Sigma\Delta\varepsilon_b = 217 \times 10^{-6}$. The time-hardening rule predicts that the strain rate in the aluminum alloy is a function of stress and creep time, so ε_a is taken from the curve for 47,600 lbf/in^2 (3.28×10^8 N/m^2), starting at $t = 0.01$ h, over a time increment of 0.04 h. Using this method, $\varepsilon_a = 110 \times 10^{-6}$, $\Delta P = 18$ lbf (80 N), and $\Delta\varepsilon_b = 50 \times 10^{-6}$. The second point on the time-hardening creep curve is then $t = \Sigma\Delta t = 0.05$ h, $\varepsilon = \Sigma\Delta\varepsilon_b = 231 \times 10^{-6}$.

This incremental process is repeated until the desired creep curve is completed.

7.4. Analytical Results

Analytical creep curves were calculated for fifteen sandwich specimens using both the strain-hardening and time-hardening rules. Both analytical curves and the experimental curve for each specimen are shown in figures 16 through 30. Analytical curves using the strain-hardening

theory could not be completed to 100 hours because creep data beyond 100 hours for the aluminum alloy were required for such computations.

8. DISCUSSION

8.1. Creep of Boron/Epoxy Material

The maximum creep strain measured in boron/epoxy in this investigation was less than 10 percent of the elastic strain in the specimen. This seems to support the view that creep in 0° unidirectional boron/epoxy is not a serious problem within the temperature range of the epoxy. The small strains measured as creep at elevated temperatures may be a result of either or both of the following:

1. Straightening of initially bowed or misoriented filaments which aline themselves as the epoxy softens

2. Fracture of individual defective filaments causing an increased stress in the remaining undamaged filaments.

These random phenomena could also explain the scatter in the creep behavior from specimen to specimen.

8.2 Creep of Aluminum Alloy

In general, the specimens tested in this investigation exhibited more creep than others reported in the literature [12, 13]. This is to be expected because of the overaging caused by the thermal preconditioning mentioned earlier.

8.3. Creep of Sandwich Specimens

Tests on sandwich specimens corroborated the supposition that 7075-T6 aluminum alloy reinforced with boron/epoxy can creep at loads which are less than 75 percent of the static strength of the specimen. The results of these tests and the analysis are discussed below with respect to some of the variables in the program.

a. Effect of Fabrication Process

Generally, larger creep strains were observed in the specimens fabricated by the co-curing process than in those fabricated by the two-step process (see table 4). This can probably be attributed to the large (21,600 lbf/in^2 at 75 °F, 1.49 x 10^8 N/m^2 at 24 °C) residual tensile stresses induced in the aluminum alloy by the co-curing process. Since the specimens fabricated by the two-step process have a limited temperature capability and the residual stresses in the co-cured specimens are

less at higher temperatures, the co-curing process may be the preferable process for applications above about 150 °F (66 °C), while the two-step process may be preferable for applications below 150 °F (66 °C).

b. Effect of Composite-to-Metal Volume Ratio

The results of the tests on specimens with different composite-to-metal volume ratios supported the hypothesis that the resistance to creep is directly related to the percentage of the load carried by the fibers (fig. 14).

c. Agreement Between Experiment and Analysis

The agreement between calculated strains and experimentally determined strains seems to vary with test temperature. For tests run at 75 °F (24 °C) and 150 °F (66 °C) the analysis predicts considerably more creep strain than was observed experimentally. At 225 °F (107 °C) the agreement was excellent, and at 300 °F (149 °C) the analysis predicts about 30 percent less strain than was observed experimentally. These discrepancies are probably due to uncertainty in the value of residual stress used in the calculations, since at 75 °F (24 °C) this constitutes up to 40 percent of the total stress in the aluminum alloy, while at 300 °F (149 °C) it was negligible.

In an effort to determine the error in the value of residual stress used in the calculations, measurements on three additional co-cured sandwich specimens were made after the completion of the test program reported herein, using the method described previously. The results of the four tests on co-cured specimens are given in table 6. The average of the four test results in considerably lower than the value used in the calculations, but the scatter between specimens is so large that the use of the average value in the calculations may not yield much better results for any given specimen. Figure 31 shows two analytical curves, one using the value of residual stress determined from the one original measurement, and one using the average value of the four measurements, compared with the experimental curve for Specimen BA-23. While the agreement between the experimental curve and calculated curve is better when the average value of residual stress is used, the discrepancy is still considerable, and this still may be because the residual stress for that particular specimen was much less than the average value used. To solve this problem, some nondestructive method of determining the residual stress in each specimen to be tested is needed. A more fruitful solution would result from research leading to the development of specimen preparation techniques which permit the residual stress to be controlled closely.

d. Comparison of Strain-Hardening and Time-Hardening Rules

For the tests at the lower three temperatures, there is little or no difference between the creep curves calculated using the strain-hardening rule and those calculated using the time-hardening rule. This was because the creep strains in the aluminum alloy, ε_a, were all in the secondary (steady-state) stage, and it doesn't matter if the translation from one creep curve to another is along a constant time line or a constant strain line.

For the tests at 300 °F (149 °C), the creep strains in the aluminum alloy were larger, entering the tertiary stage (increasing creep rate) of the curves. According to the strain-hardening rule, the translation from one curve to another is along a constant strain line. Since the slopes of the curves are increasing, this gives a higher value of ε_a than the time-hardening rule, by which the translation is along a constant time line. Thus, after the aluminum alloy has entered tertiary-stage creep, the strain-hardening rule predicts more creep strain in the sandwich specimens than does the time-hardening rule. If creep data for the aluminum alloy specimens were available substantially beyond 100 hours, the strain-hardening curves for the sandwich specimens could have been calculated to 100 hours, and, judging from the slopes of these curves, the correlation with the experimental curves would have improved with increased time.

9. CONCLUSIONS

Based on the experiments and analyses covered by this report the following conclusions are drawn:

1. Creep is not a problem in 0° unidirectional boron/epoxy at temperatures below 300 °F (149 °C) because the filaments, which previous work has shown not to creep at these temperatures, carry approximately 98 percent of the load. The maximum creep strain observed in boron/epoxy in the investigation was less than 10 percent of the elastic strain.

2. Creep can be a problem in 7075-T6 aluminum alloy reinforced with 0° unidirectional boron/epoxy even at temperatures below 300 °F (149 °C) and loads below 75 percent of the static strength of the specimen. Stress relaxation in the aluminum alloy causes a continuously increasing percentage of the total load to be carried by the composite, resulting in an increased elastic strain which may be called "creep".

3. The amount of creep in a sandwich specimen is directly related to the percentage of the total load carried by the aluminum alloy. In tests run with initial conditions of 300 °F (149 °C), 40,000 lbf/in^2 (2.76×10^8 N/m^2) applied stress in the aluminum alloy and 131,000 lbf/in^2 (9.04×10^8 N/m^2) applied stress in the boron/epoxy, a sandwich specimen with a composite-to-metal volume ratio of 0.18 ruptured after 1.8 hours with 2410×10^{-6} creep strain, while a specimen with a ratio of 1.17 had not ruptured after 265 hours with 1920×10^{-6} creep strain.

4. Analytical curves calculated using the strain-hardening rule generally give somewhat better agreement with experimental results than the curves calculated using the time-hardening rule.

5. The analysis described in this report predicts creep curves which are insufficiently accurate to allow their use in design. However, the shortcoming may not be in the analysis itself, but rather in the inaccuracy of the values of residual stress which are used in the calculations.

The author would like to express his gratitude to Dr. Leonard Mordfin at the National Bureau of Standards for his encouragement and many helpful suggestions throughout this program.

10. REFERENCES

[1] Fechek, F. J., Advanced Composites Efforts-A Status Report of Air Force Programs with Graphite Reinforced Composites, Paper 71-DE-13, ASME, (April 1971).

[2] Ellison, E. G. and Boone, D. H., Journal of Less Common Metals, Vol. 13, 103-111 (1967).

[3] Shockey, P. D., Hofer, K. E., and Wright, D. W., Structural Airframe Applications of Advanced Composite Materials, Vol. IV-Mechanical Properties-Static. AFML TR 69-101, Vol. IV (Oct. 1969).

[4] Lou, Y. C. and Schapery, R. A., Viscoelastic Behavior of a Nonlinear Fiber Reinforced Plastic, AFML TR 70-113, (May 1970).

[5] Breinan, E. M. and Kreider, K. G., Axial Creep and Stress Rupture of B-Al Composites, Metallurgical Transactions, Vol. 1, 93-104, (Jan. 1970).

[6] Toth, I. J., Creep and Fatigue Behavior of Unidirectional and Cross-plied Composites, Composite Materials: Testing and Design, ASTM STP 460, American Society for Testing and Materials, 236-353 (1969).

[7] Menke, G. D. and Toth, I. J., The Time Dependent Mechanical Behavior of Composite Materials, AFML TR 70-174, (1970).

[8] Mordfin, L., Analytical Study of Creep Deflection of Structural Beams, NASA TN D-661, (1960).

[9] Mordfin, L. and Halsey, N., Experimental Investigation of Creep Deflection of Extruded and Riveted I-Beams, NASA TN D-662, (1960).

[10] Popov, E. P., Bending of Beams with Creep, Jour. of Applied Physics, Vol. 20, No. 3, 251-256, (March 1949).

[11] Hayashi, T., On the Law of Mixture of Creep Strength of Fiber Reinforced Composite Materials, Trans. Japan Society for Aeronautical and Space Sciences, Vol. 10, No. 17, 54-58, (1967).

[12] Heimerl, G. J. and McEvily, A. J., Generalized Master Curves for Creep and Rupture, NACA TN 4112, (1957).

[13] Heimerl, G. J. and Farquhar, J., Compressive and Tensile Creep of 7075-T6 and 2024-T3 Aluminum Alloy Sheet, NASA TN D-160, (1959).

Table 1 - Results from Tension Tests on Boron/Epoxy and 7075-T6 Aluminum Alloy Specimens.

Test temperature °F	Specimen number: Boron/Epoxy	Specimen number: Aluminum alloy	Fiber content by volume percent	Elastic modulus lbf/in^2	Maximum strength lbf/in^2
75	B-5	-	54	31.3×10^6	195,000
75	B-9	-	54	32.7	199,000
150	B-15	-	47	30.3	190,000
150	B-17	-	47	31.5	177,000
225	B-13	-	47	31.9	162,000[a]
225	B-16	-	47	32.7	160,000[a]
300	B-6	-	54	(b)	179,000
300	B-14	-	47	32.0	166,000[a]
75	-	A-1	-	9.83×10^6	74,000
75	-	A-2	-	9.63	(b)
75	-	A-4	-	9.35	(b)
150	-	A-8	-	9.94	71,000
225	-	A-9	-	10.0	62,000

[a] failed in grip

[b] measurement not made

Table 2 - Results of Tensile Creep Tests on Boron/Epoxy Specimens.

Test temperature	Stress	Specimen No.	Fiber content by volume	Total creep strain	Duration of test	Failure
°F	lbf/in^2		percent	10^{-6}	h	
75	150,000	B-24	52	0	0.5	(a)
75	150,000	B-25	52	115	160	none
75	175,000	B-26	52	0	0	(b)
150	150,000	B-23	52	80	140	none
150	175,000	B-22	52	0	0	(b)
150	175,000	B-19	47	40	4.6	(c)
225	125,000	B-30	50	0	1.5	(d)
225	125,000	B-31	50	60	20.5	(c)
225	150,000	B-18	47	460	120	none
225	150,000	B-20	47	0	6.2	(c)
300	125,000	B-27	52	0	0	(b)
300	150,000	B-21	52	0	0	(b)

(a) Failed in gage section.

(b) Failed in gage section upon application of load.

(c) Failed partially in grip.

(d) Slipped out of end tabs.

Table 3 - Results of Tensile Creep Tests on 7075-T6 Aluminum Alloy Specimens.

Test temperature	Stress	Specimen No.	Total creep strain	Duration of test	Failure
°F	lbf/in²		10^{-6}	h	
75	50,000	A-11[(a)]	430	100	none
75	60,000	A-13	1,120	150	none
150	30,000	A-33	110	100	none
150	40,000	A-18	510	137	none
150	50,000	A-17	3,880	100	none
225	30,000	A-25	980	110	none
225	35,000	A-28	1,500	119	none
225	40,000	A-19	1,840	100	none
225	45,000	A-34	3,290	115	none
225	48,000	A-35	110,000	13.2	Rupture
225	50,000	A-23	105,000	0.7	Rupture
300	10,000	A-36	320	100	none
300	20,000	A-27	1,390	140	none
300	30,000	A-24	23,750	110	none
300	35,000	A-29	87,500	16.6	Rupture
300	40,000	A-26	110,000	2.1	Rupture
300	44,000	A-32	116,000	0.6	Rupture

[(a)] Specimen A-11 did not undergo thermal treatment prior to testing. All other specimens were exposed to 325 °F (163 °C) for 1 hour and 350 °F (177 °C) for 5 hours prior to testing.

Table 4 - Results of Tensile Creep Tests on 7075-T6 Aluminum Alloy Sandwich Specimens with 4 Plies of Boron/ Epoxy.

Test temperature	Test load	Average stress	Specimen No.	Fabrication process	Nominal stress in aluminum	Nominal stress in boron/epoxy	Total creep strain	Duration of test	Failure
°F	lbf	lbf/in^2			lbf/in^2	lbf/in^2	10^{-6}	h	
75	2250	50,000	BA-23	co-curing	30,000	98,000	75	100	none
75	2895	66,000	BA-22	co-curing	40,000	131,000	120	100	none
75	3645	82,000	BA- 3	two-step	50,000	167,000	75	100	none
75	3675	82,000	BA- 4	two-step	50,000	163,000	0	100	none
150	2050	48,000	BA-18	co-curing	30,000	98,000	205	100	none
150	2550	61,000	BA-12	two-step	40,000	131,000	100	16.5	(a)
150	2714	64,000	BA-32	co-curing	40,000	131,000	500	118	none
150	3150	73,000	BA-33	co-curing	45,000	147,000	845	100	none
150	3105	75,000	BA- 9	two-step	50,000	163,000	0	0	(b)
150	3585	81,000	BA-10	two-step	50,000	163,000	65	0.5	(a)
150	4145	96,000	BA-21	co-curing	60,000	196,000	0	0	(b)
225	2210	50,000	BA-15	co-curing	30,000	98,000	635	104	none
225	2450	57,000	BA-29	co-curing	35,000	114,000	695	97	none
225	2740	64,000	BA-16	co-curing	40,000	131,000	1460	115	none
225	3370	75,000	BA-24	co-curing	45,000	147,000	0	0	(b)
225	3535	81,000	BA-17	co-curing	50,000	163,000	0	0	(b)
300	2050	48,000	BA-19	co-curing	30,000	98,000	885	100	none
300	2245	50,000	BA-31	co-curing	35,000	114,000	2240	100	none
300	2815	65,000	BA-20	co-curing	40,000	131,000	1665	11.5	(c)

(a) Failed in grip.

(b) Failed in gage section upon application of load.

(c) Failed in gage section.

Table 5 - Results of Tensile Creep Tests on 7075-T6 Aluminum-Alloy Sandwich Specimens with Various Composite-to Metal Volume Ratios.

Test temperature	Average stress	Test load	Specimen No.	Plies of boron/epoxy	Composite-to-metal volume ratio	Nominal stress in aluminum	Nominal stress in boron/epoxy	Total creep strain	Duration of test	Failure
°F	lbf/in^2	lbf				lbf/in^2	lbf/in^2	10^{-6}	h	
300	54,000	2000	BA-25	2	0.18	40,000	131,000	2410	1.8	(a)
300	65,000	2815	BA-20	4	0.38	40,000	131,000	1670	11.5	(a)
300	72,000	3490	BA-27	6	0.54	40,000	131,000	1980	109	(a)
300	80,000	4520	BA-37	8	0.79	40,000	131,000	1850	46	(a)
300	82,000	4595	BA-38	8	0.78	40,000	131,000	478	3	(b)
300	89,000	6080	BA-39	12	1.17	40,000	131,000	1920	265	none

(a) Failed in gage section.

(b) Failed in grip.

Table 6 - Residual Strains at 75 °F in Aluminum Alloy of Co-cured Sandwich Specimens.

Specimen No.	Residual strain in aluminum
BA-30	$+2270 \times 10^{-6}$
BA-28	+1590
BA-34	+ 733
BA-35	+ 848
Average	$+1360 \times 10^{-6}$
Analytical (based on $\alpha_b = 2.8 \times 10^{-6}/°F$ $\alpha_a = 13.6 \times 10^{-6}/°F$)	$+1650 \times 10^{-6}$

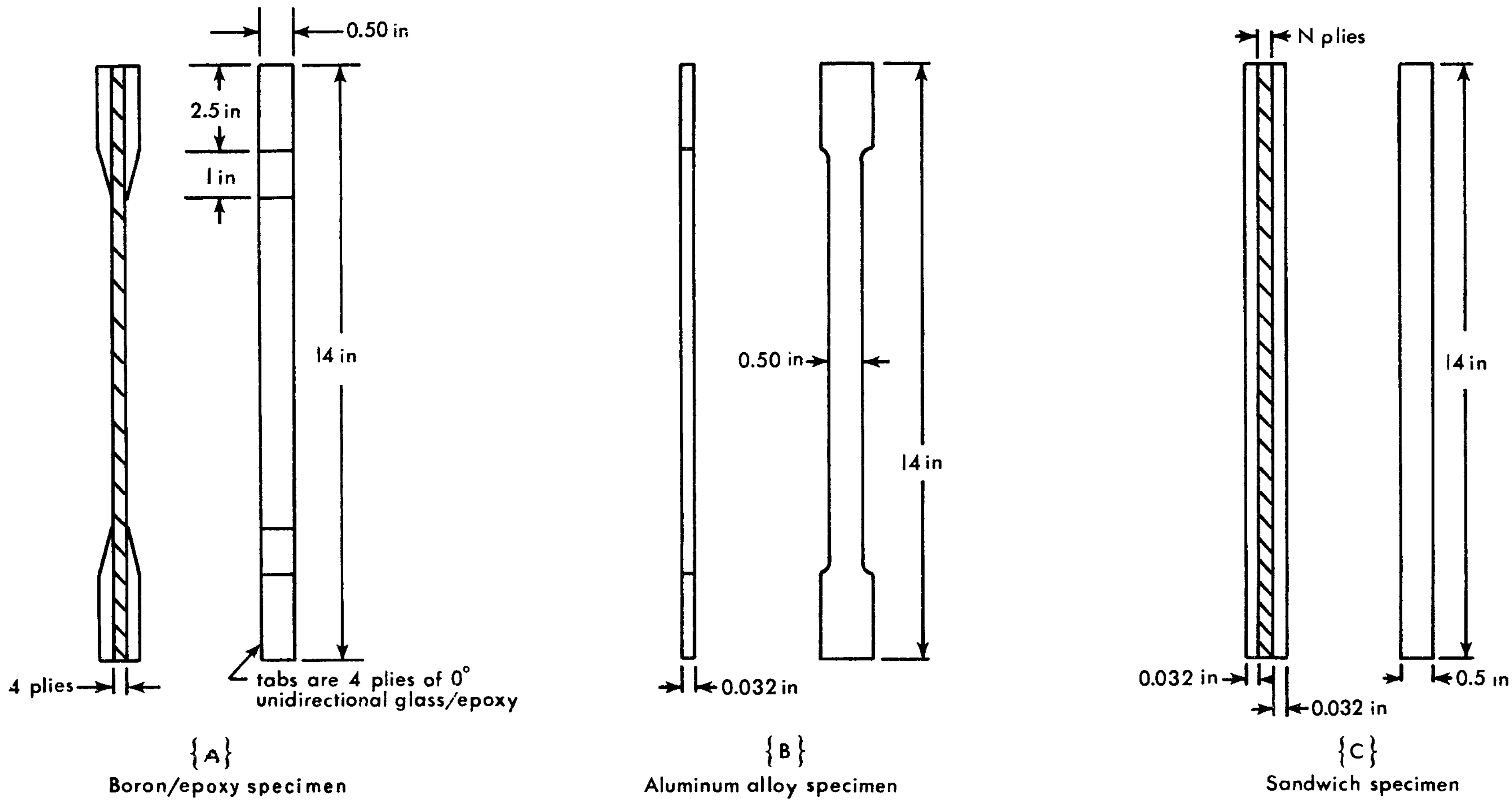

FIGURE 1 - Specimen geometries for creep tests.

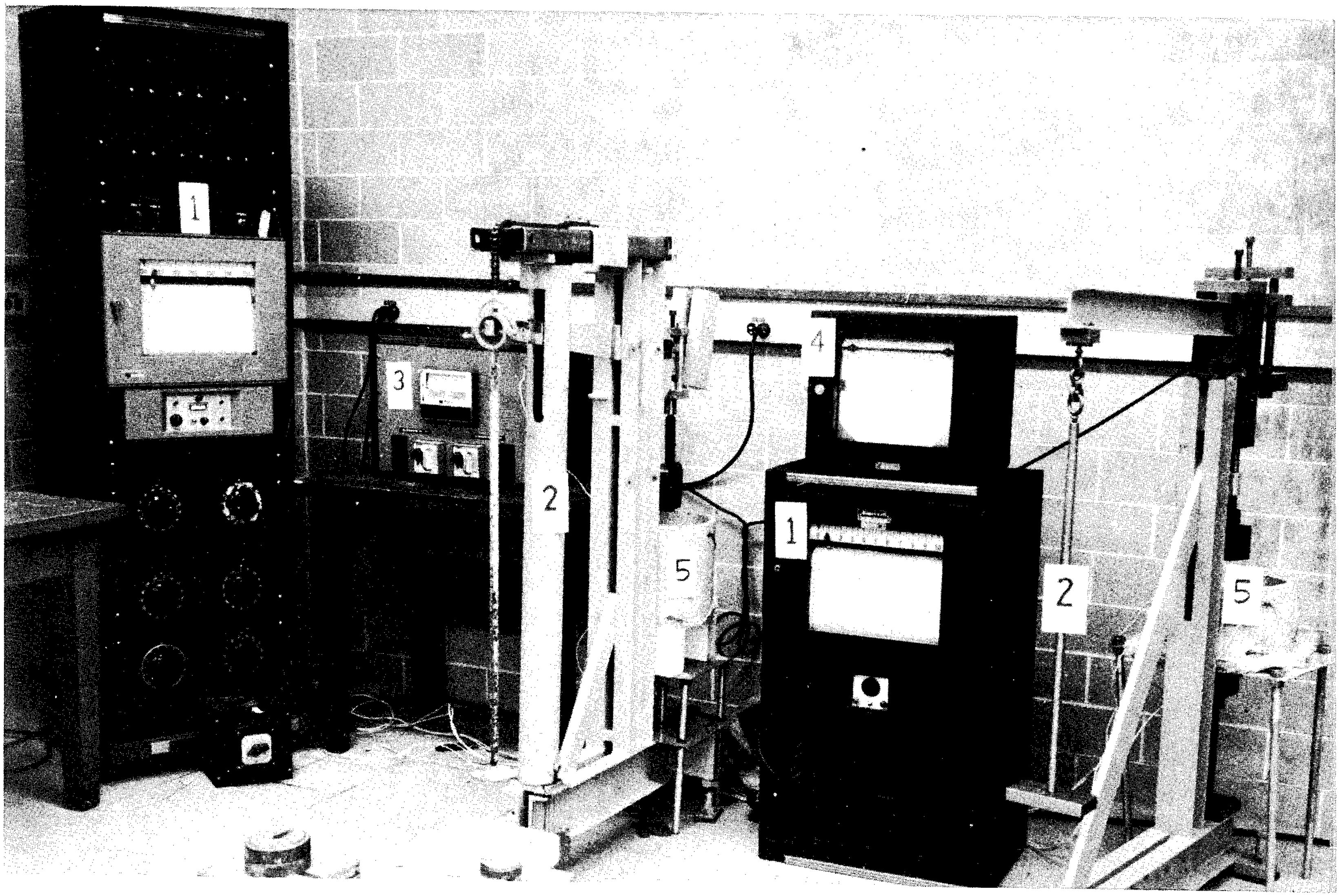

FIGURE 2 - Laboratory test set-up showing 1) temperature controllers, 2) deadweight creep testing machines, 3) high sensitivity extensometer (LVDT) recorder, 4) low sensitivity extensometer recorder, and 5) test furnaces.

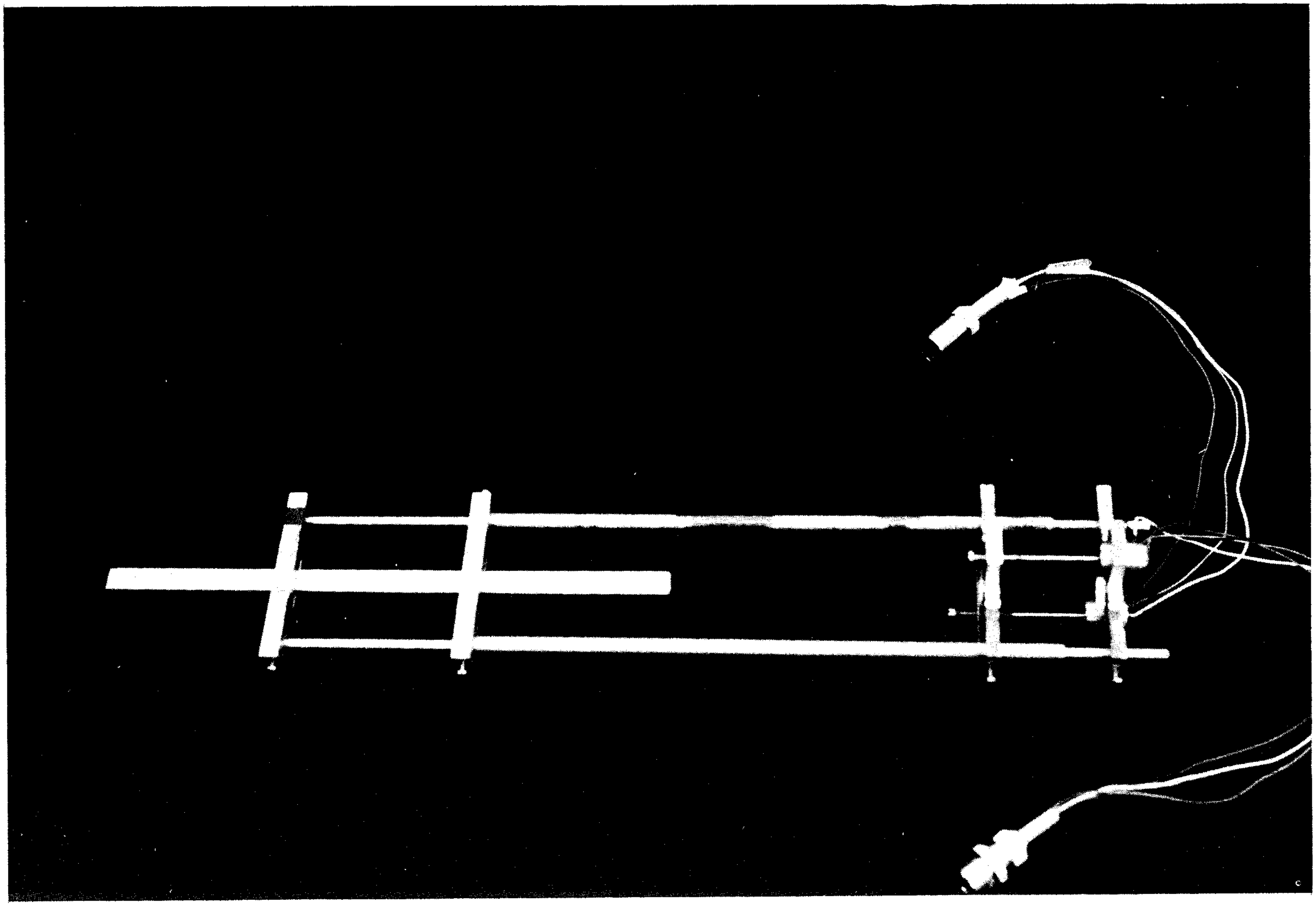

FIGURE 3 - Sandwich specimen with extension rods and high sensitivity extensometer sensing elements (LVDT's) attached.

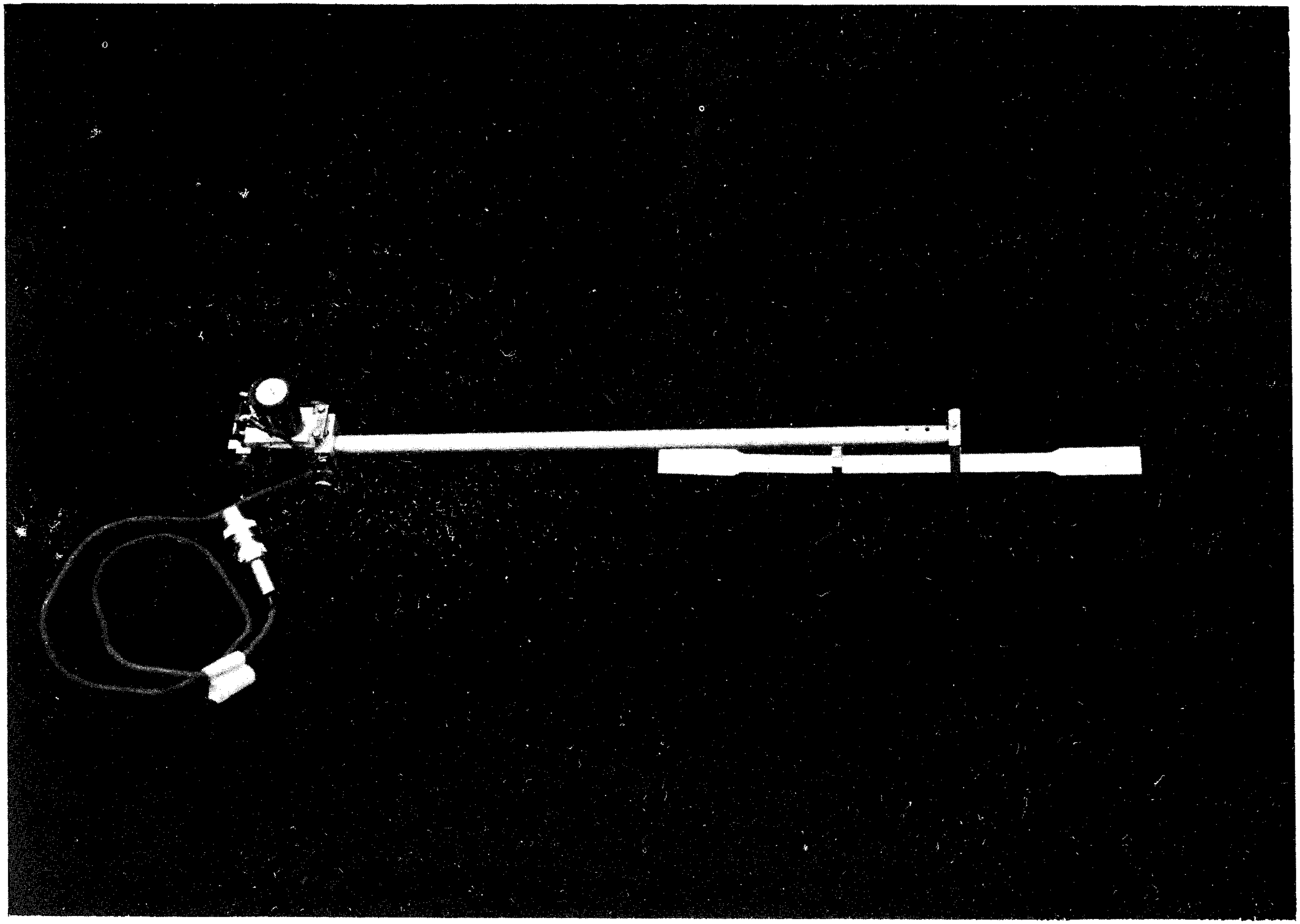

FIGURE 4 - Aluminum-alloy specimen with extension rods and low sensitivity extensometer attached.

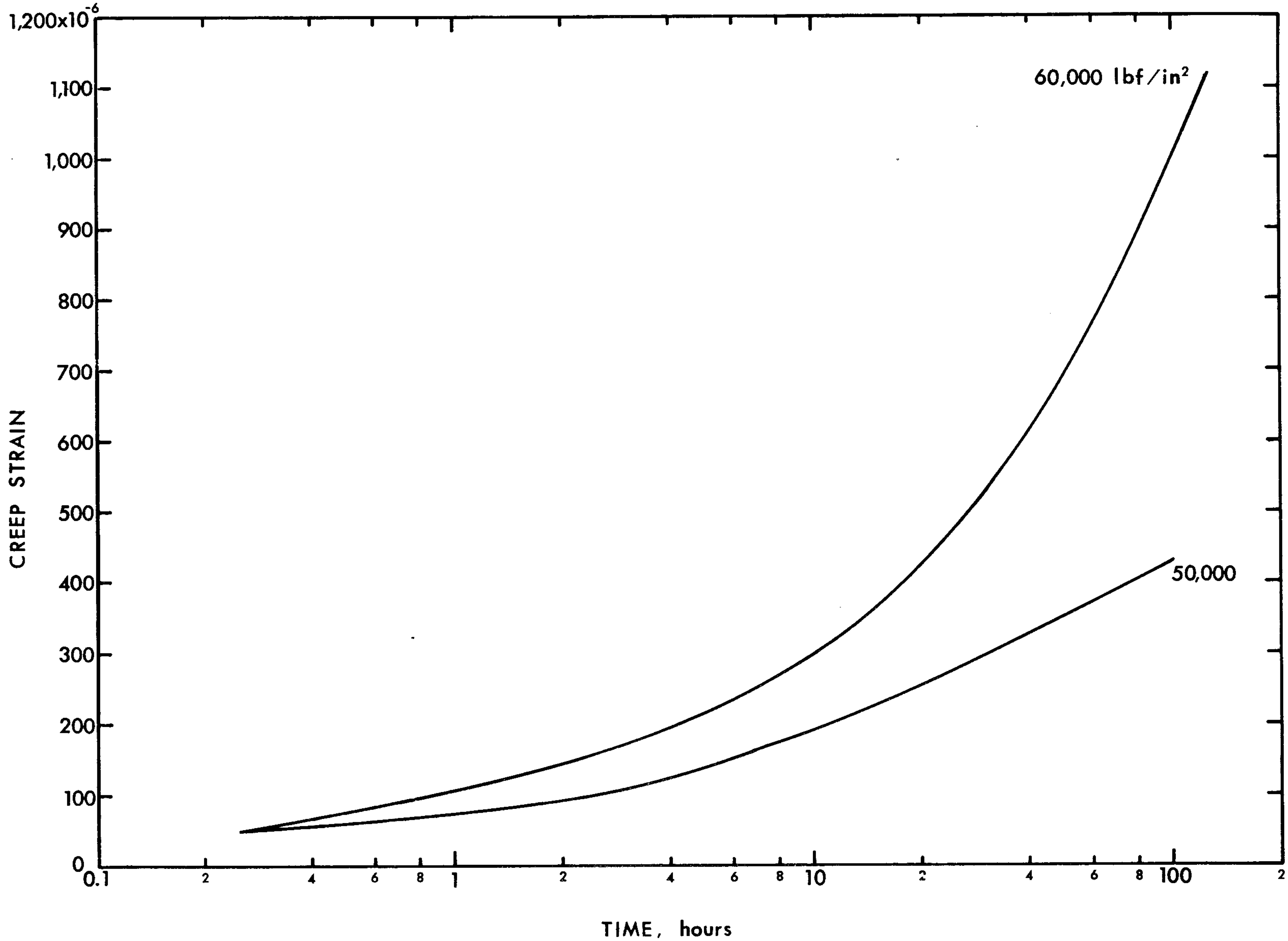

FIGURE 5 - Tensile creep curves for preconditioned 7075-T6 aluminum alloy at 75 °F (24 °C).

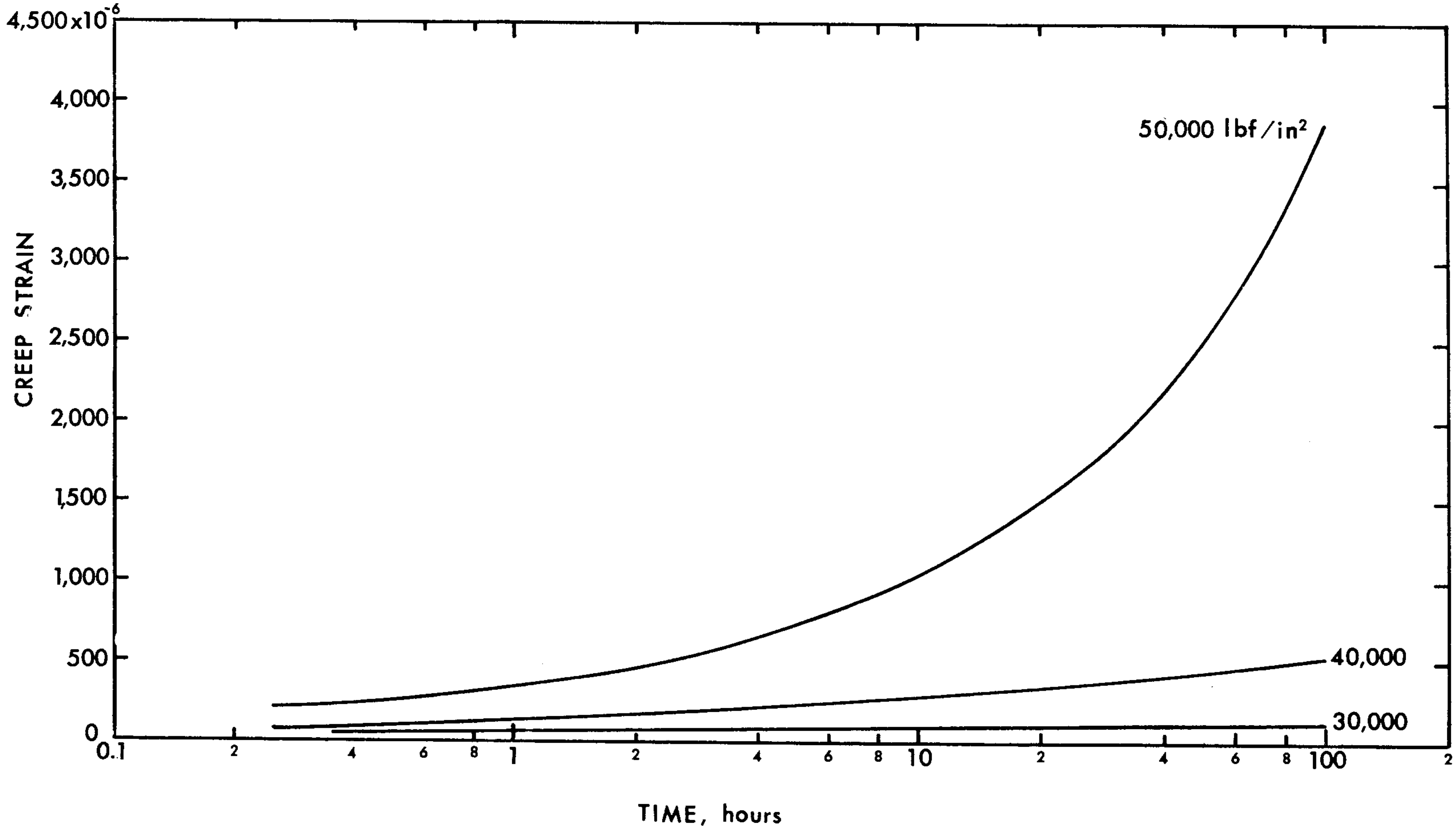

FIGURE 6 - Tensile creep curves for preconditioned 7075-T6 aluminum alloy at 150 °F (66 °C).

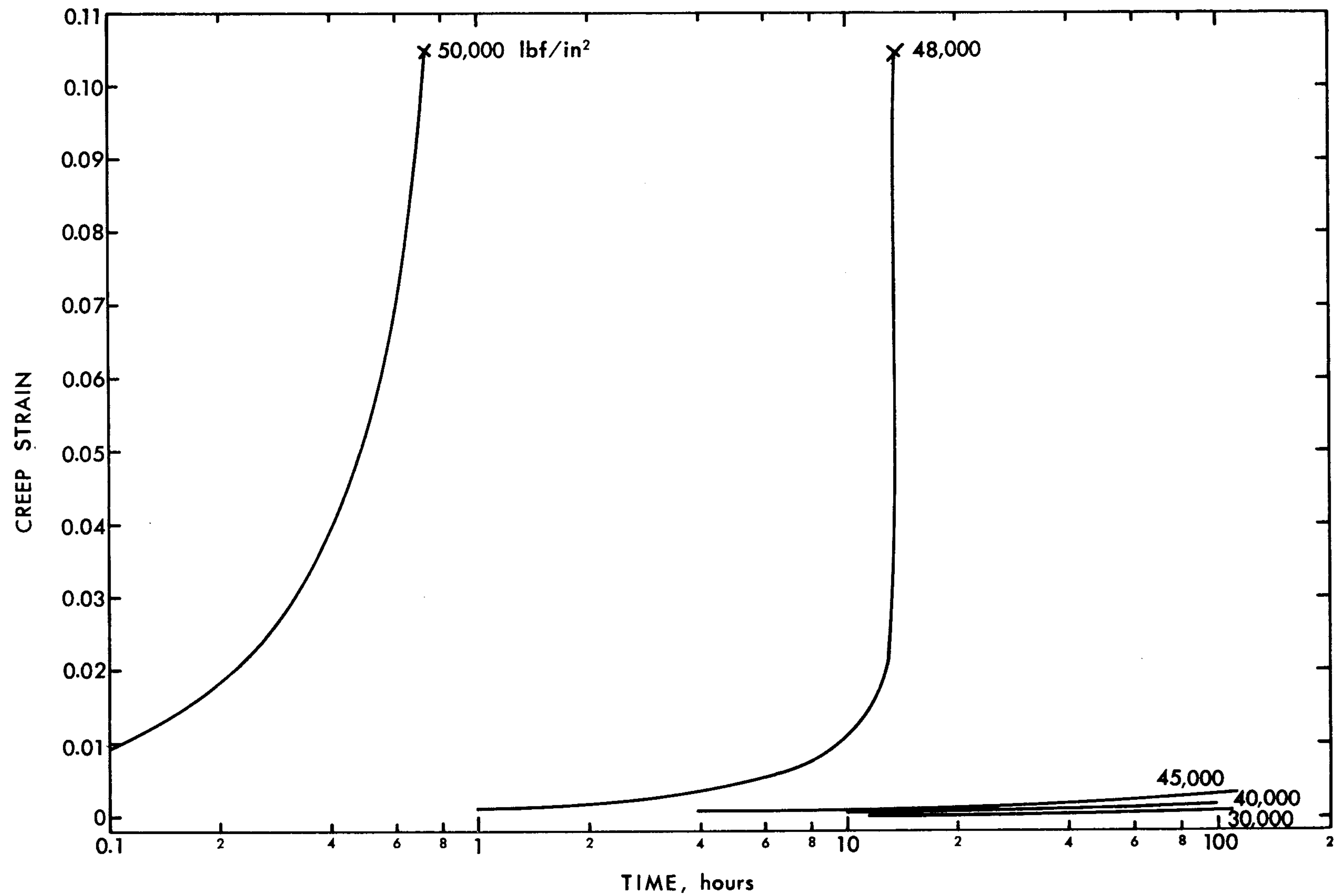

FIGURE 7 - Tensile creep curves for preconditioned 7075-T6 aluminum alloy at 225 °F (107 °C).

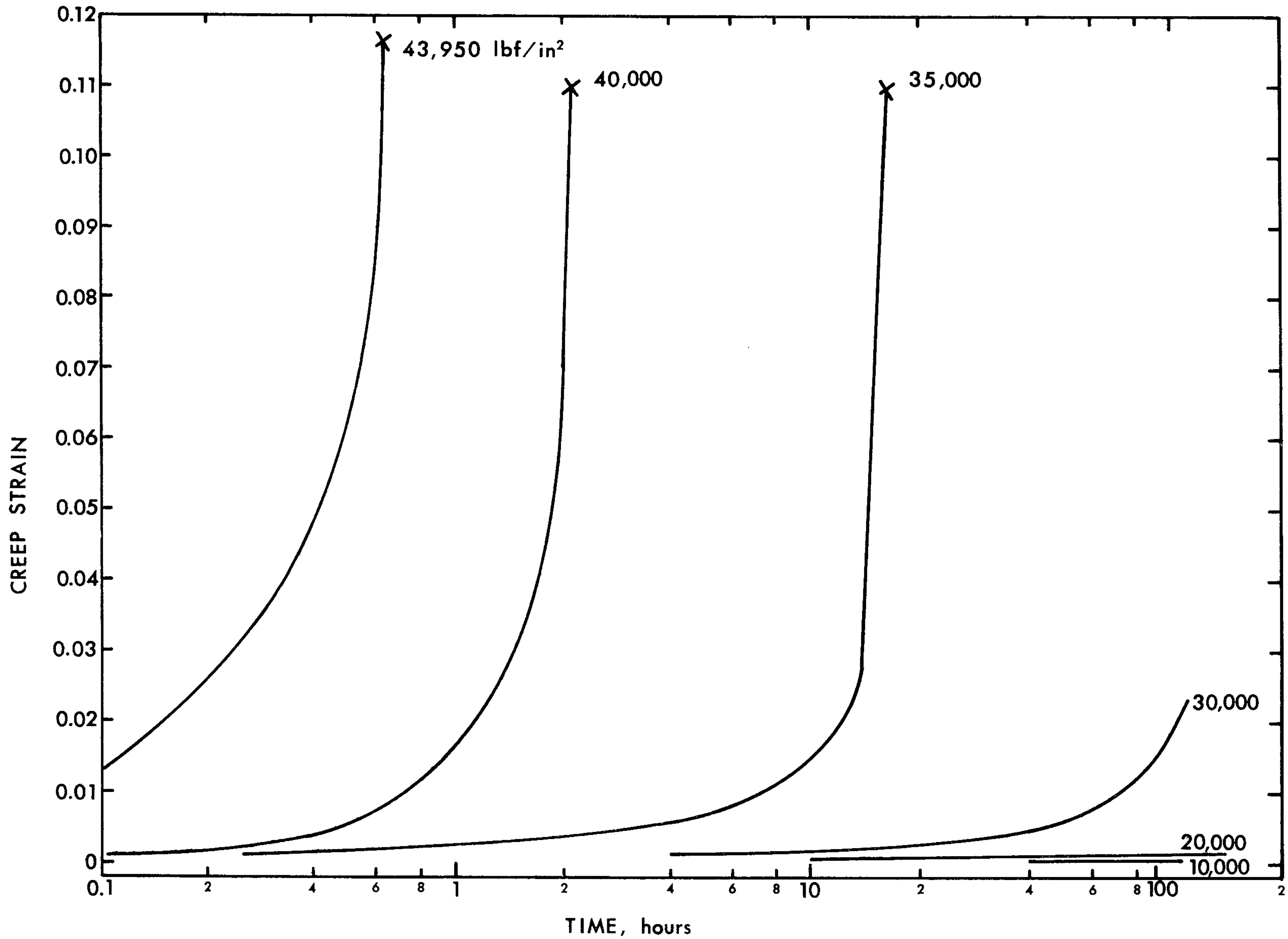

FIGURE 8 - Tensile creep curves for preconditioned 7075-T6 aluminum alloy at 300 °F (149 °C).

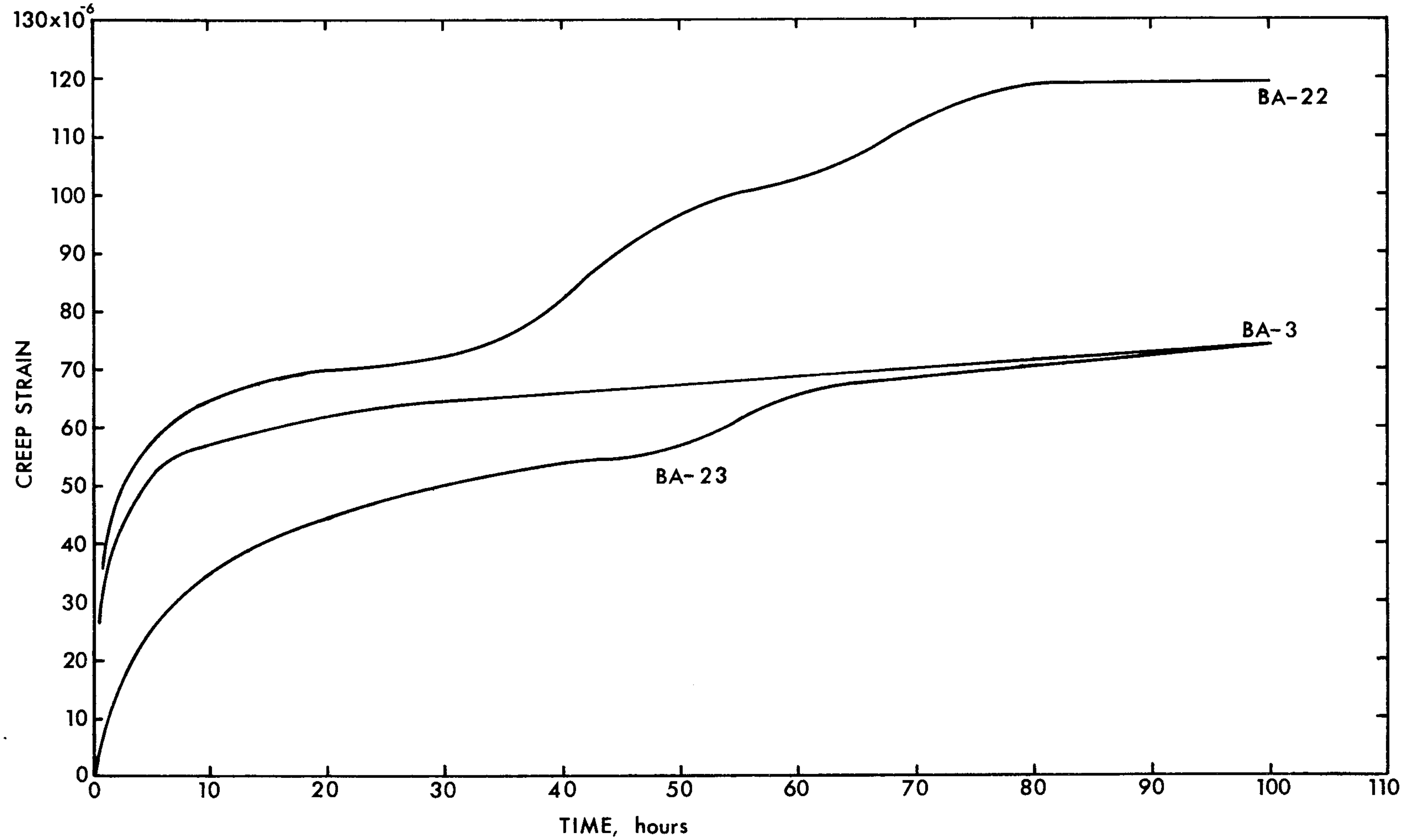

FIGURE 9 - Tensile creep curves for boron/epoxy reinforced 7075-T6 aluminum alloy with a 0.38 composite-to-metal volume ratio at 75 °F (24 °C). Specimen loading conditions are given in table 4.

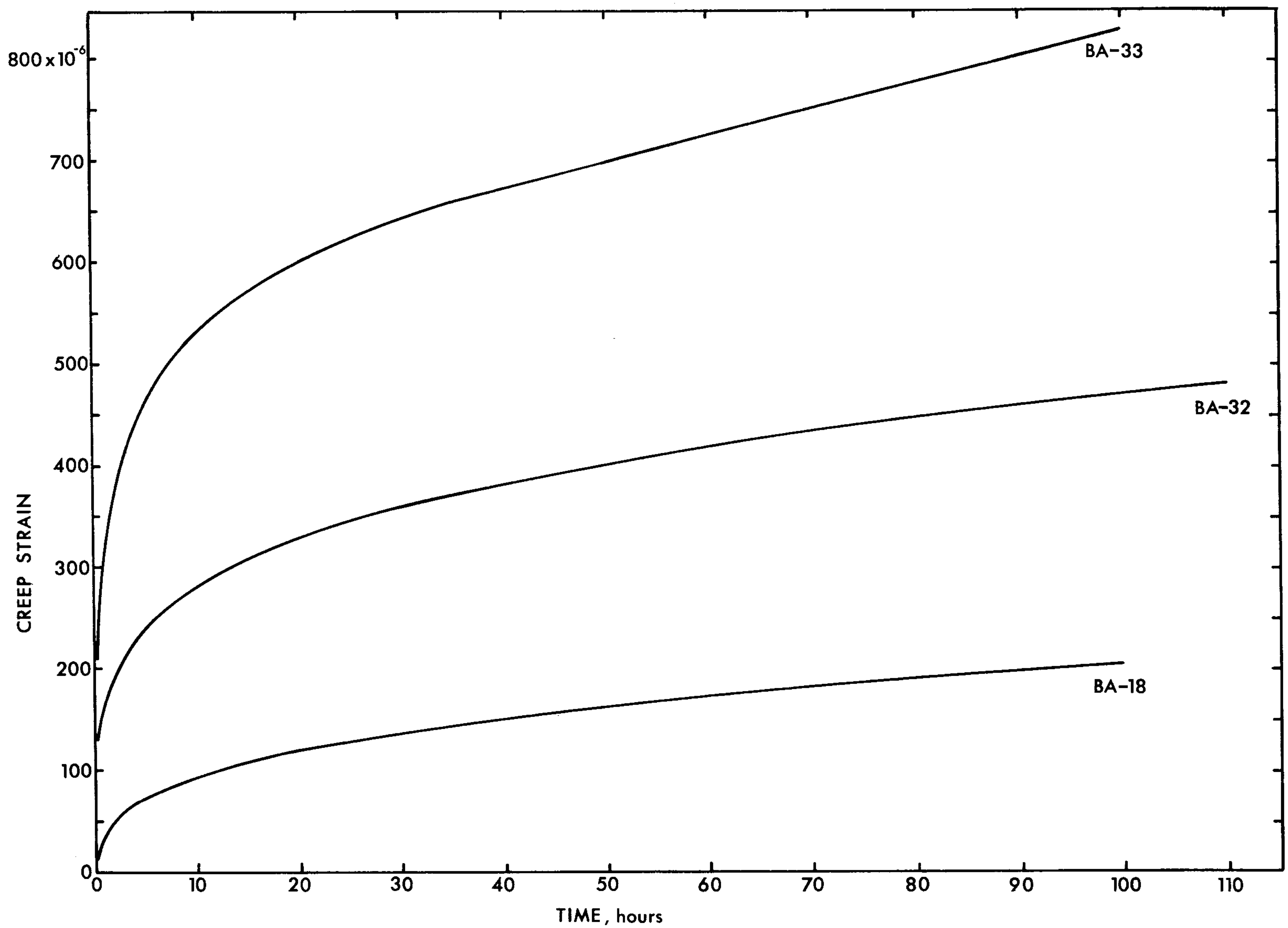

FIGURE 10 - Tensile creep curves for boron/epoxy reinforced 7075-T6 aluminum alloy with a 0.38 composite-to-metal volume ratio at 150 °F (66 °C). Specimen loading conditions are given in table 4.

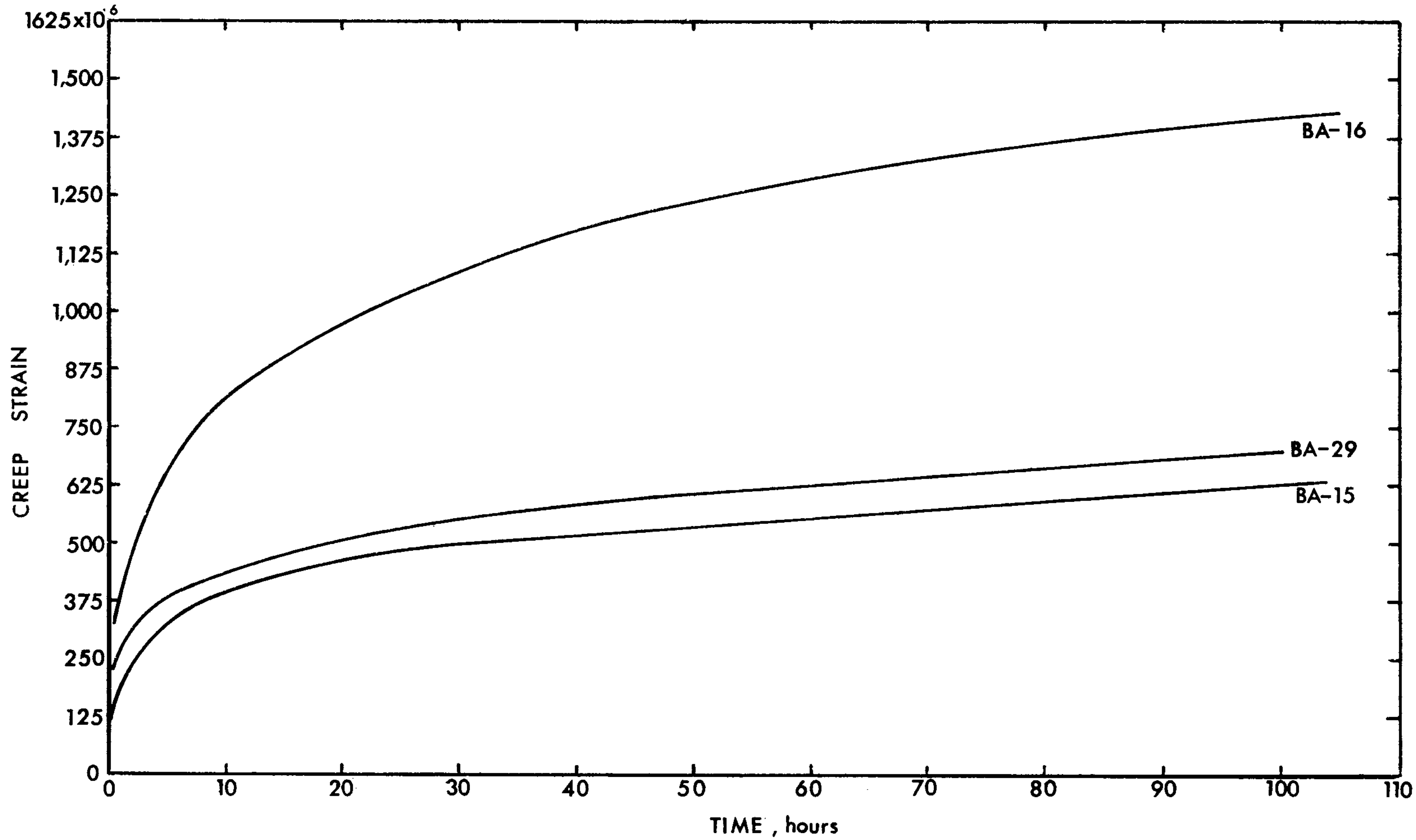

FIGURE 11 - Tensile creep curves for boron/epoxy reinforced 7075-T6 aluminum alloy with a 0.38 composite-to-metal volume ratio at 225 °F (107 °C). Specimen loading conditions are given in table 4.

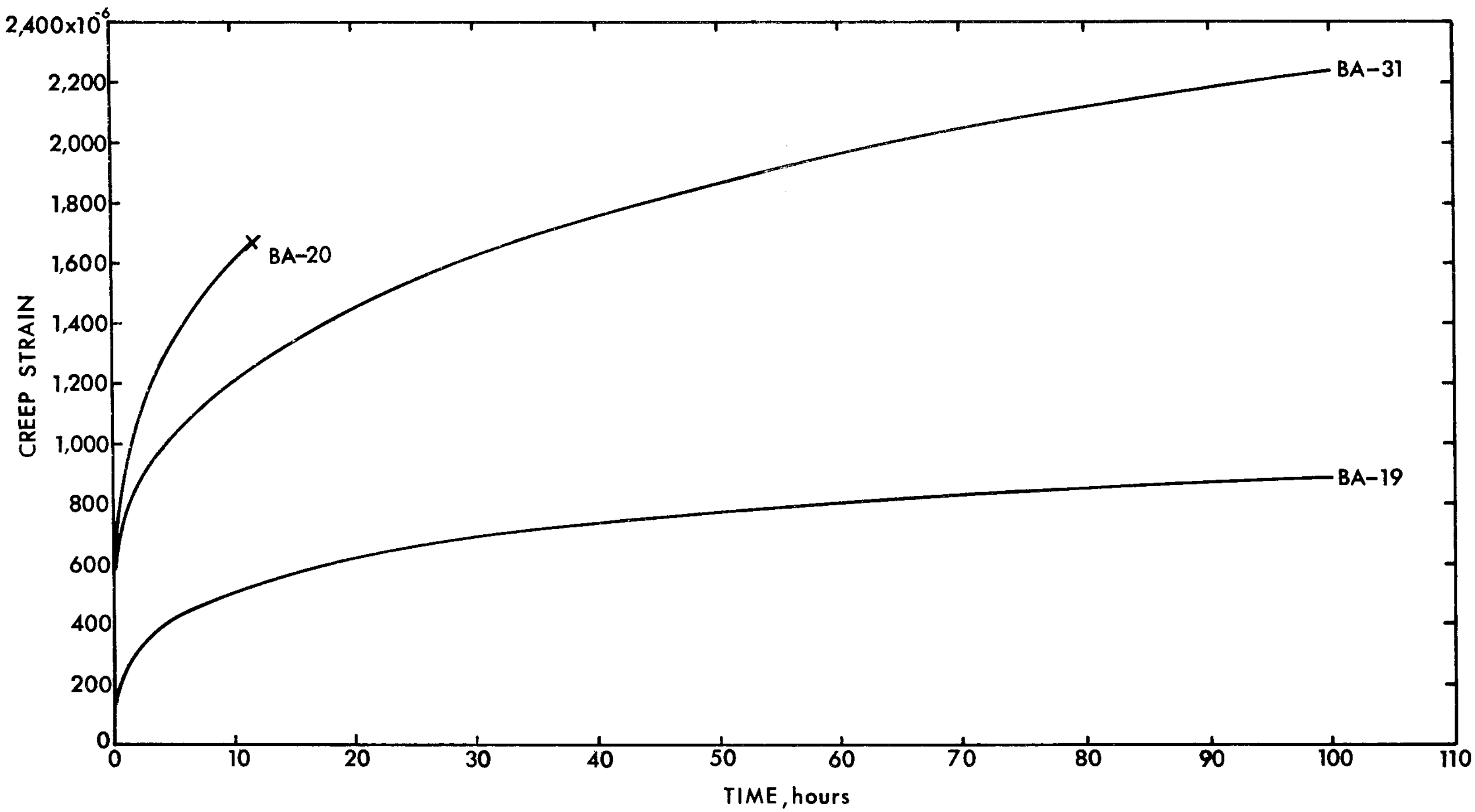

FIGURE 12 - Tensile creep curves for boron/epoxy reinforced 7075-T6 aluminum alloy with a 0.38 composite-to-metal volume ratio at 300 °F (149 °C). Specimen loading conditions are given in table 4.

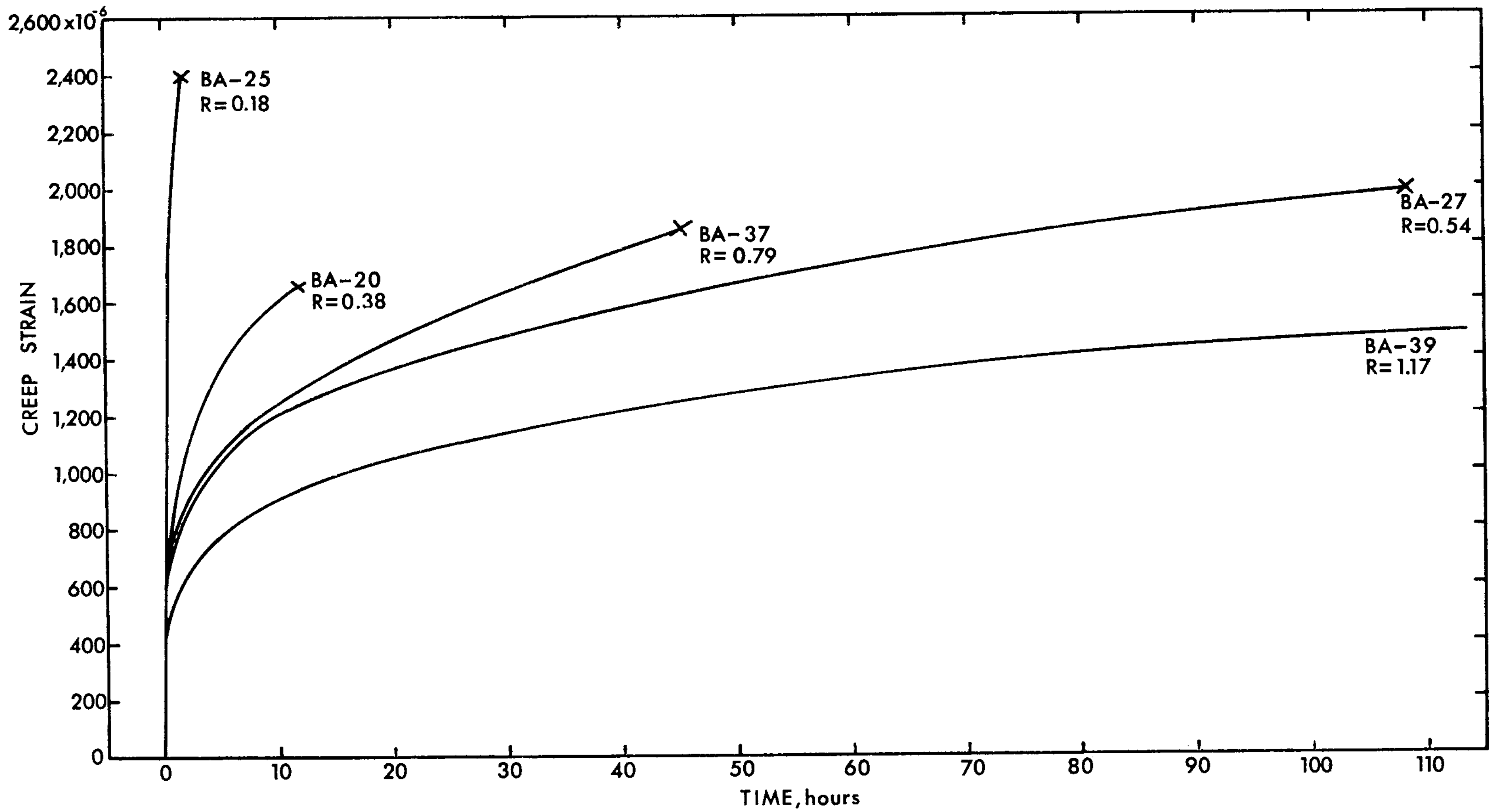

FIGURE 13 - Tensile creep curves for boron/epoxy reinforced 7075-T6 aluminum alloy with different composite-to-metal volume ratios at 300 °F (149 °C). Specimen loading conditions are given in table 5.

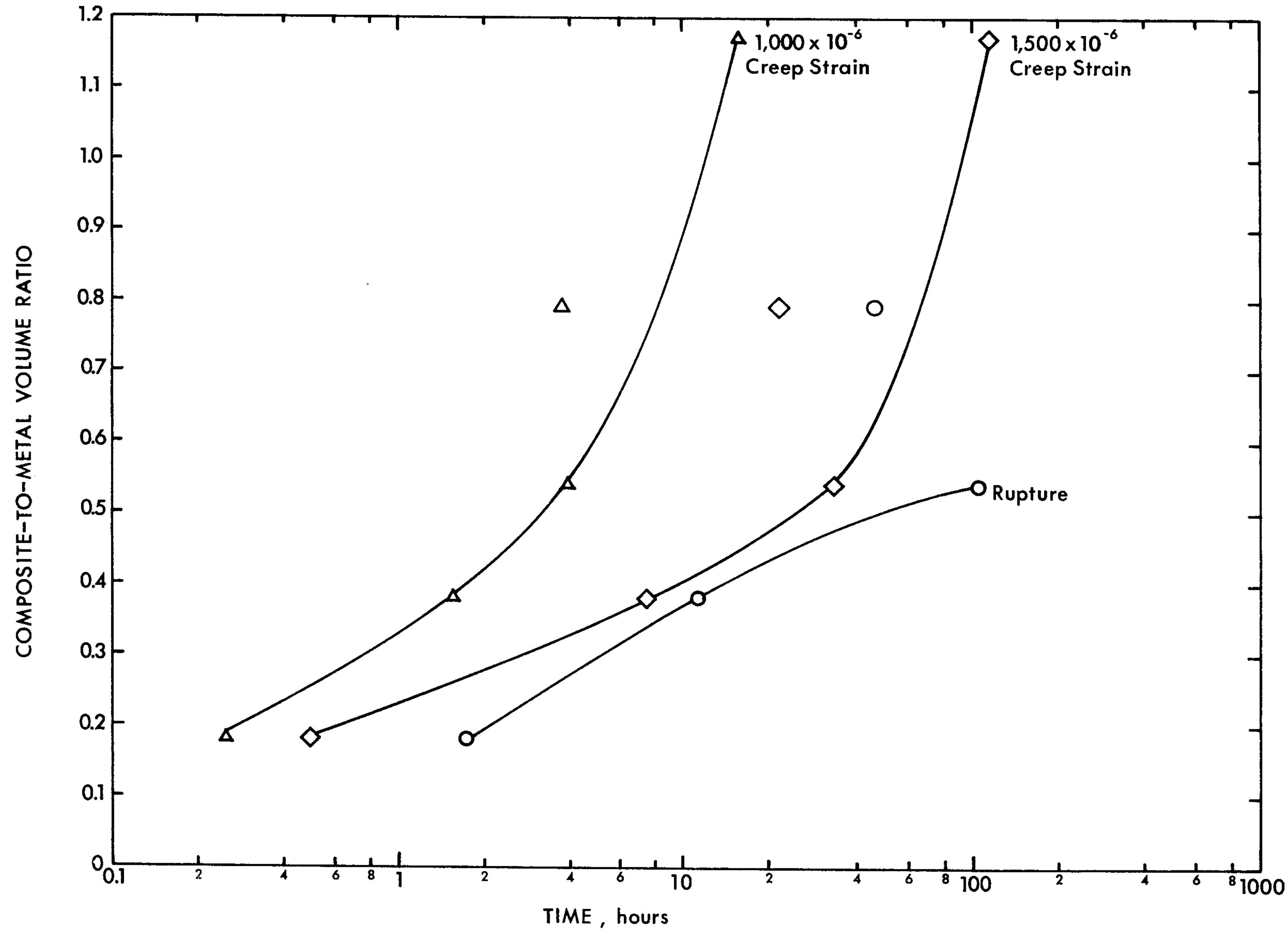

FIGURE 14 - Effect of composite-to-metal volume ratio on the creep and rupture behavior of boron/epoxy-reinforced 7075-T6 aluminum alloy.

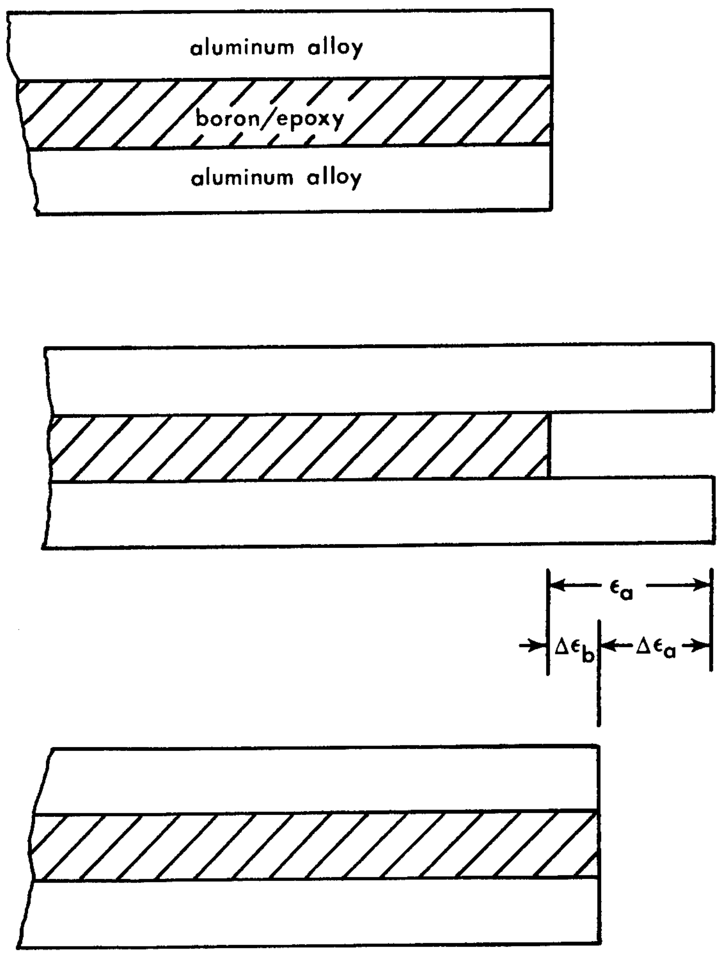

FIGURE 15 - Explanation of strain symbols used in creep analysis.

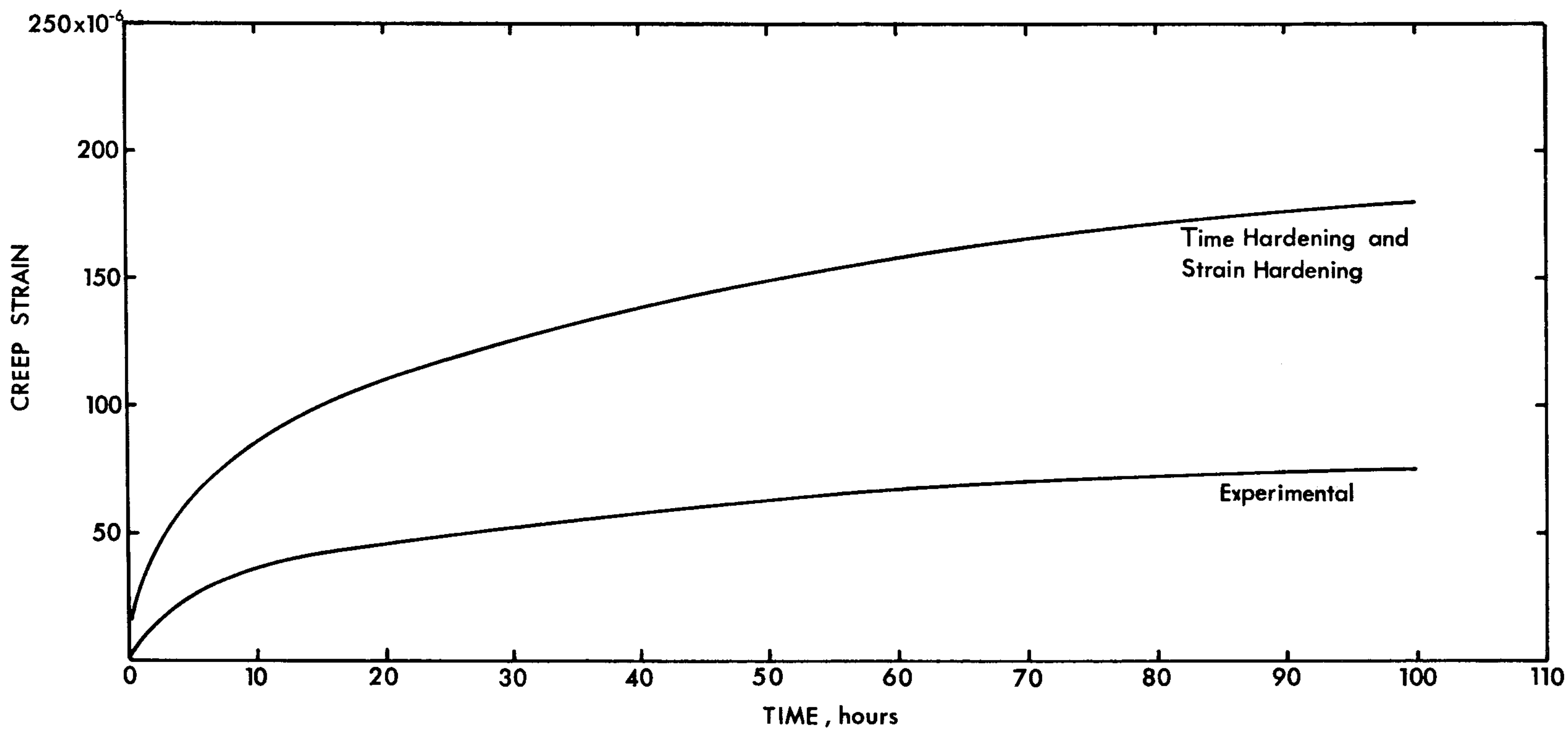

FIGURE 16 - Experimental and calculated creep curves for Specimen BA-23 (T = 75 °F, 24 °C).

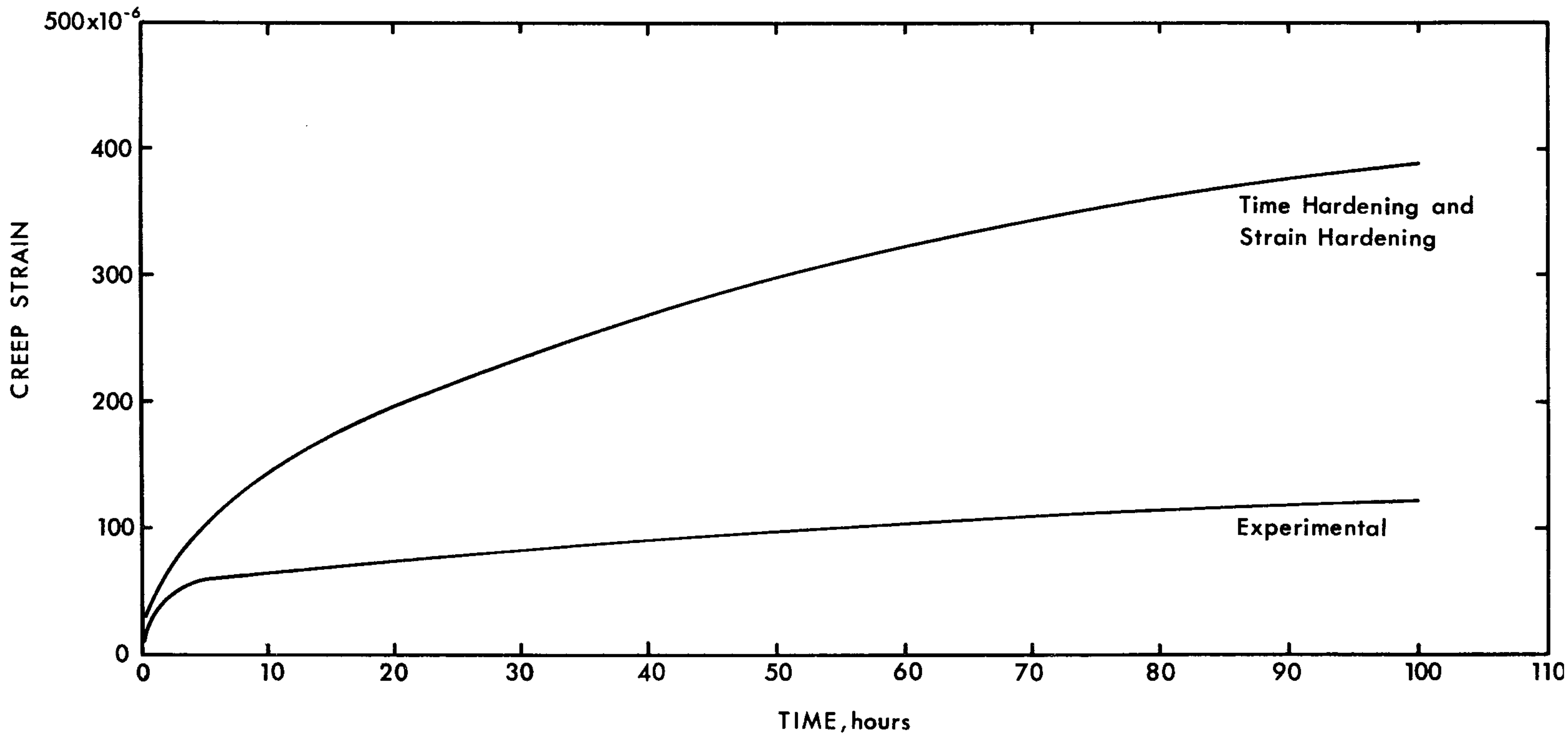

FIGURE 17 - Experimental and calculated creep curves for Specimen BA-22 (T = 75 °F, 24 °C).

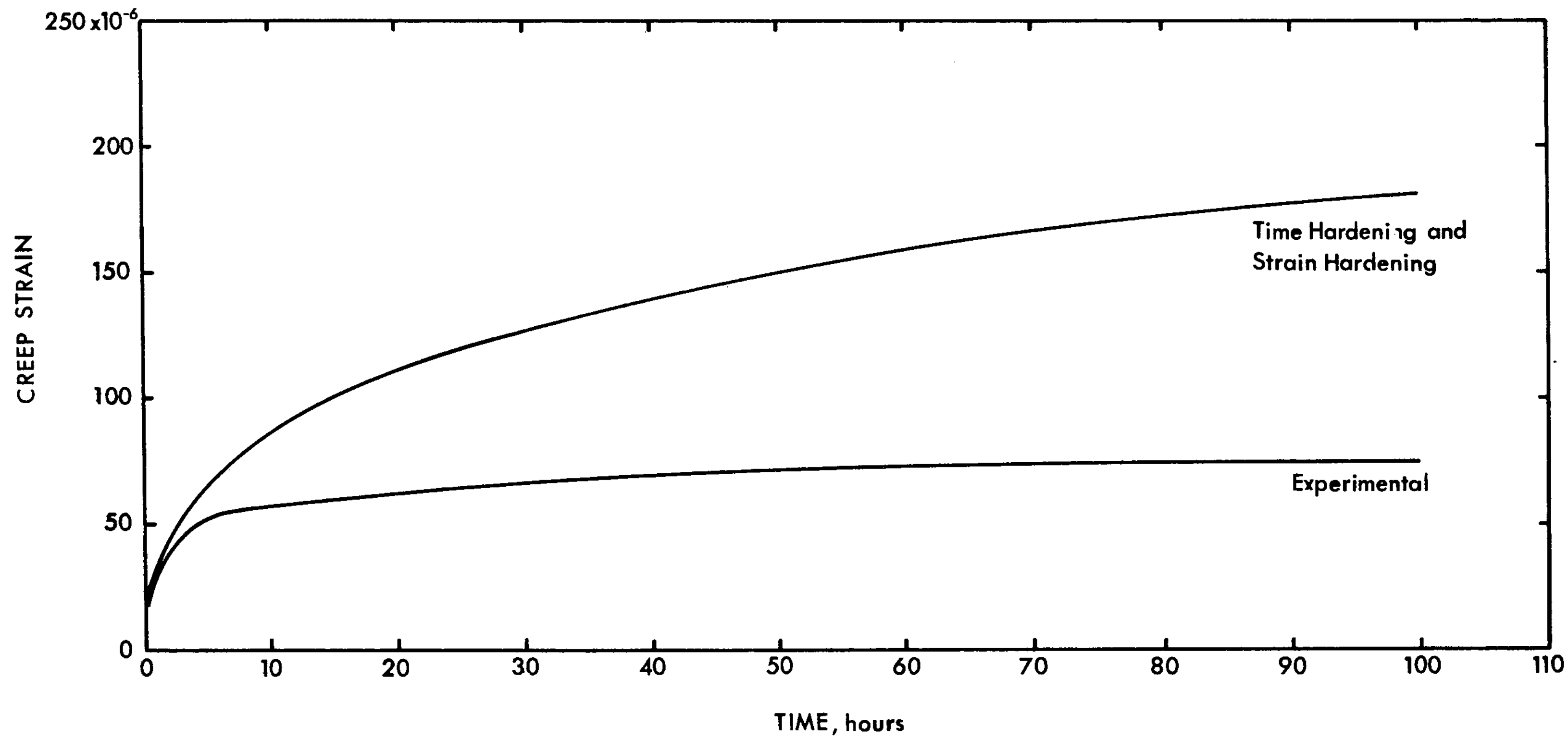

FIGURE 18 - Experimental and calculated creep curves for Specimen BA-3 (T = 75 °F, 24 °C).

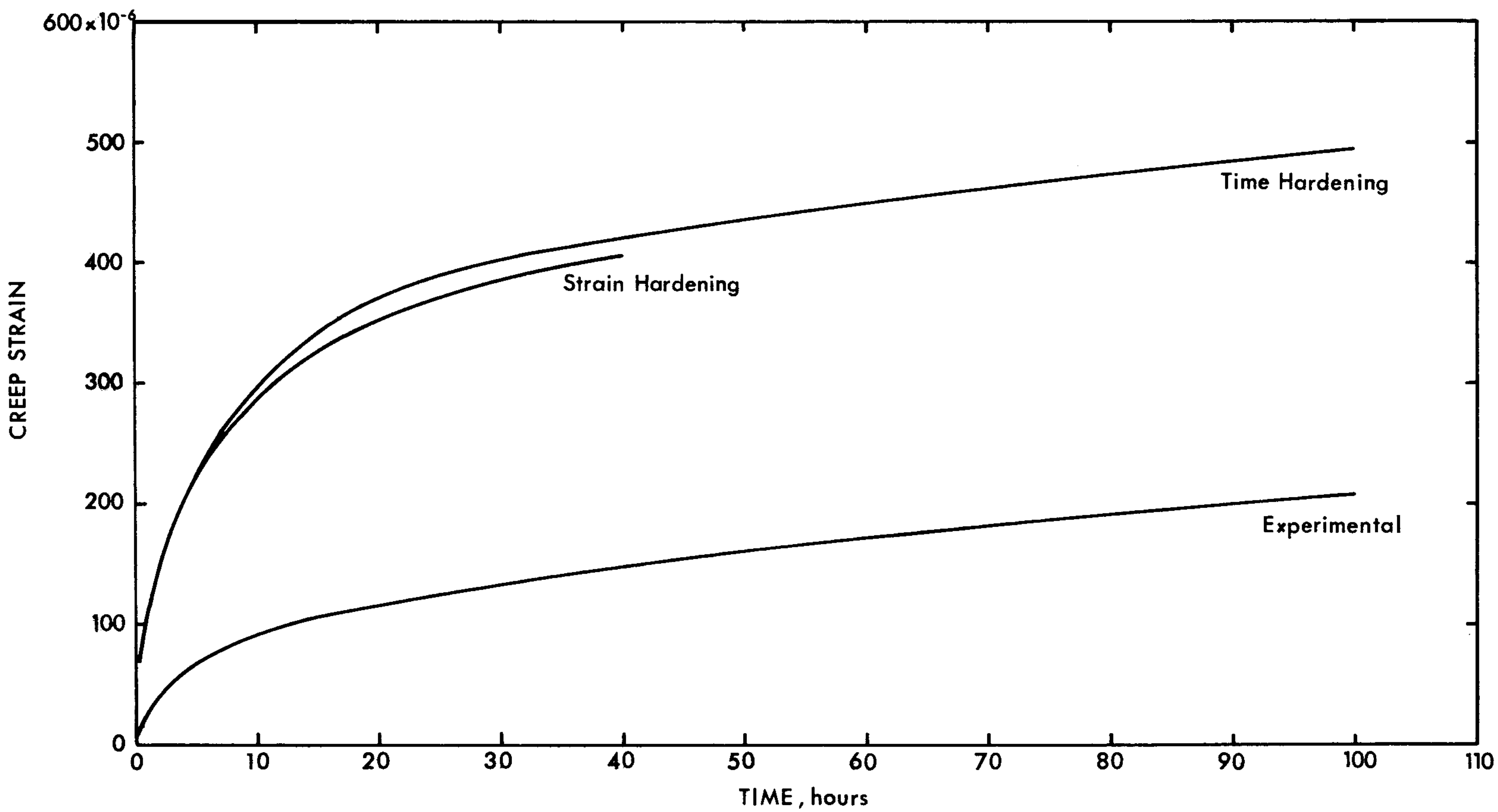

FIGURE 19 - Experimental and calculated creep curves for Specimen BA-18 (T = 150 °F, 66 °C).

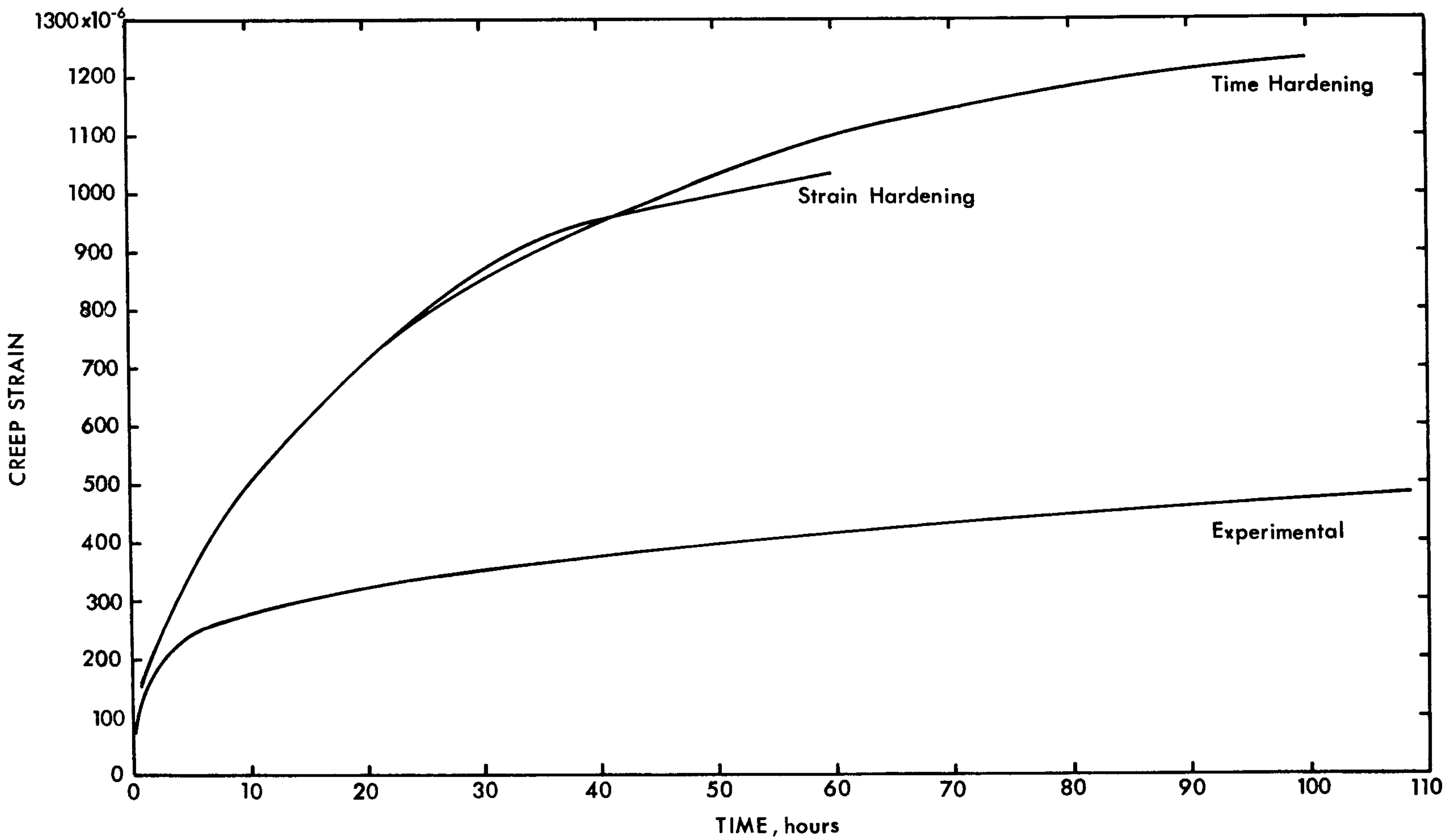

FIGURE 20 - Experimental and calculated creep curves for Specimen BA-32 (T = 150 °F, 66 °C).

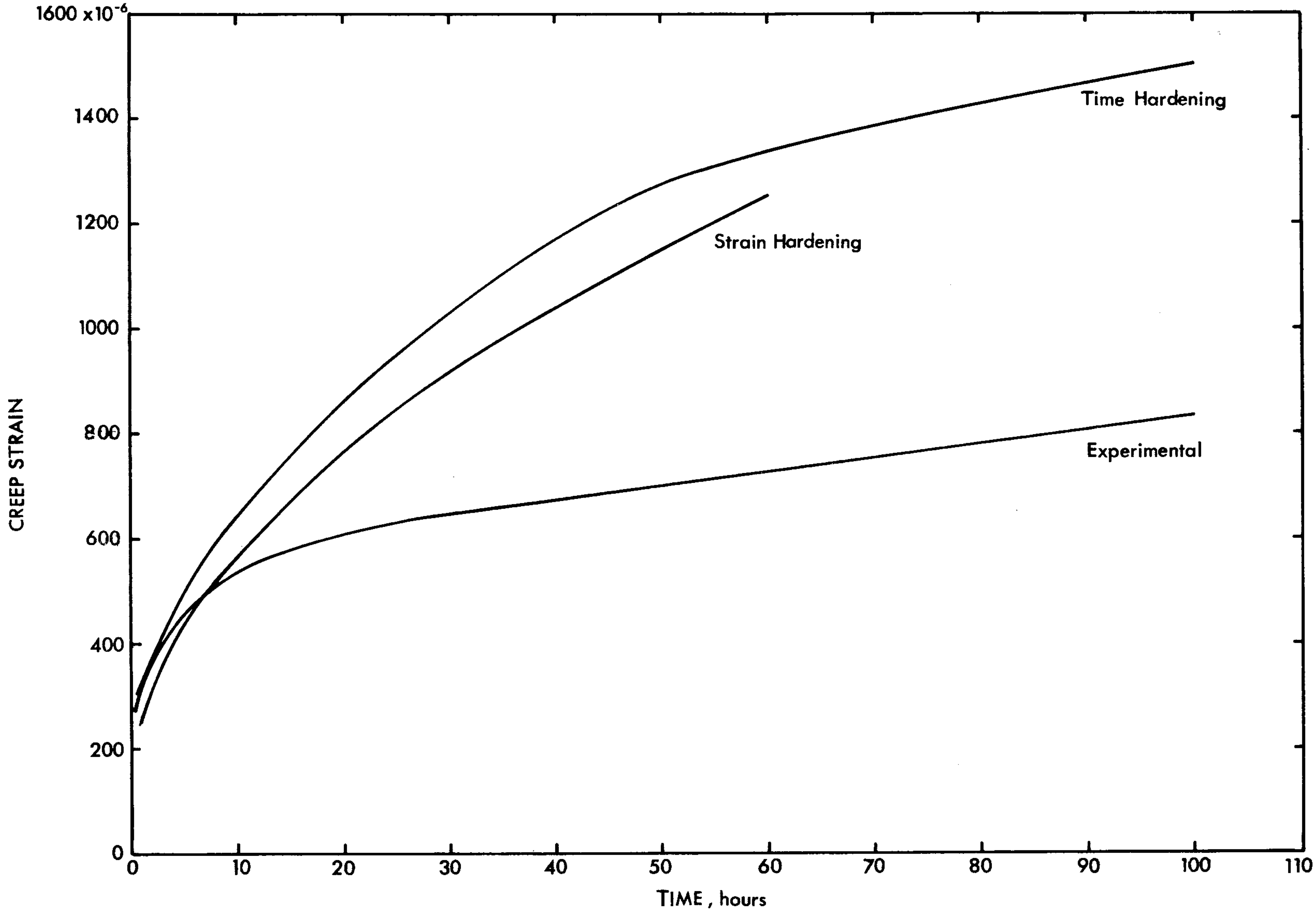

FIGURE 21 - Experimental and calculated creep curves for Specimen BA-33 (T = 150 °F, 66 °C).

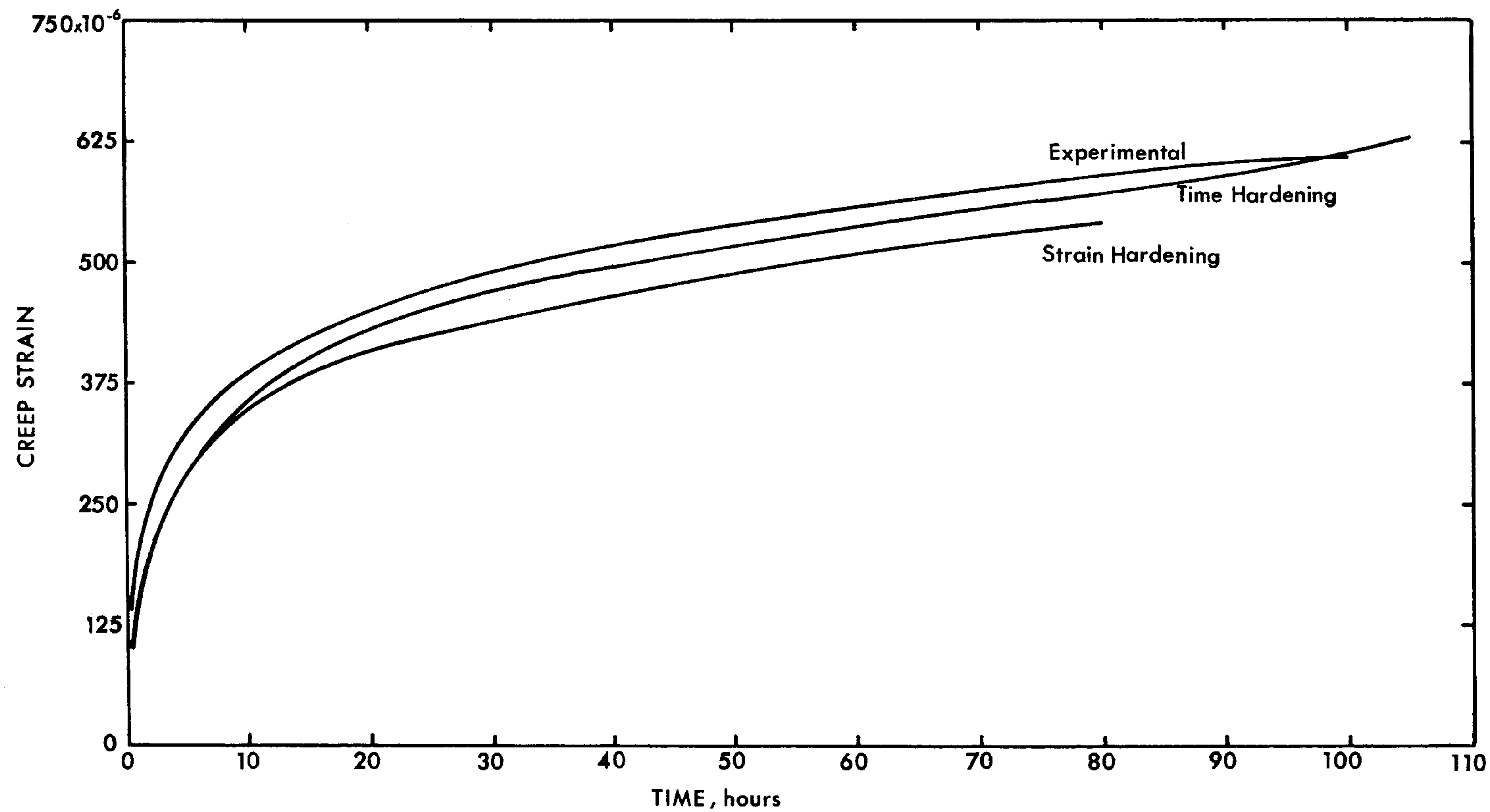

FIGURE 22 - Experimental and calculated creep curves for Specimen BA-15 (T = 225 °F, 107 °C).

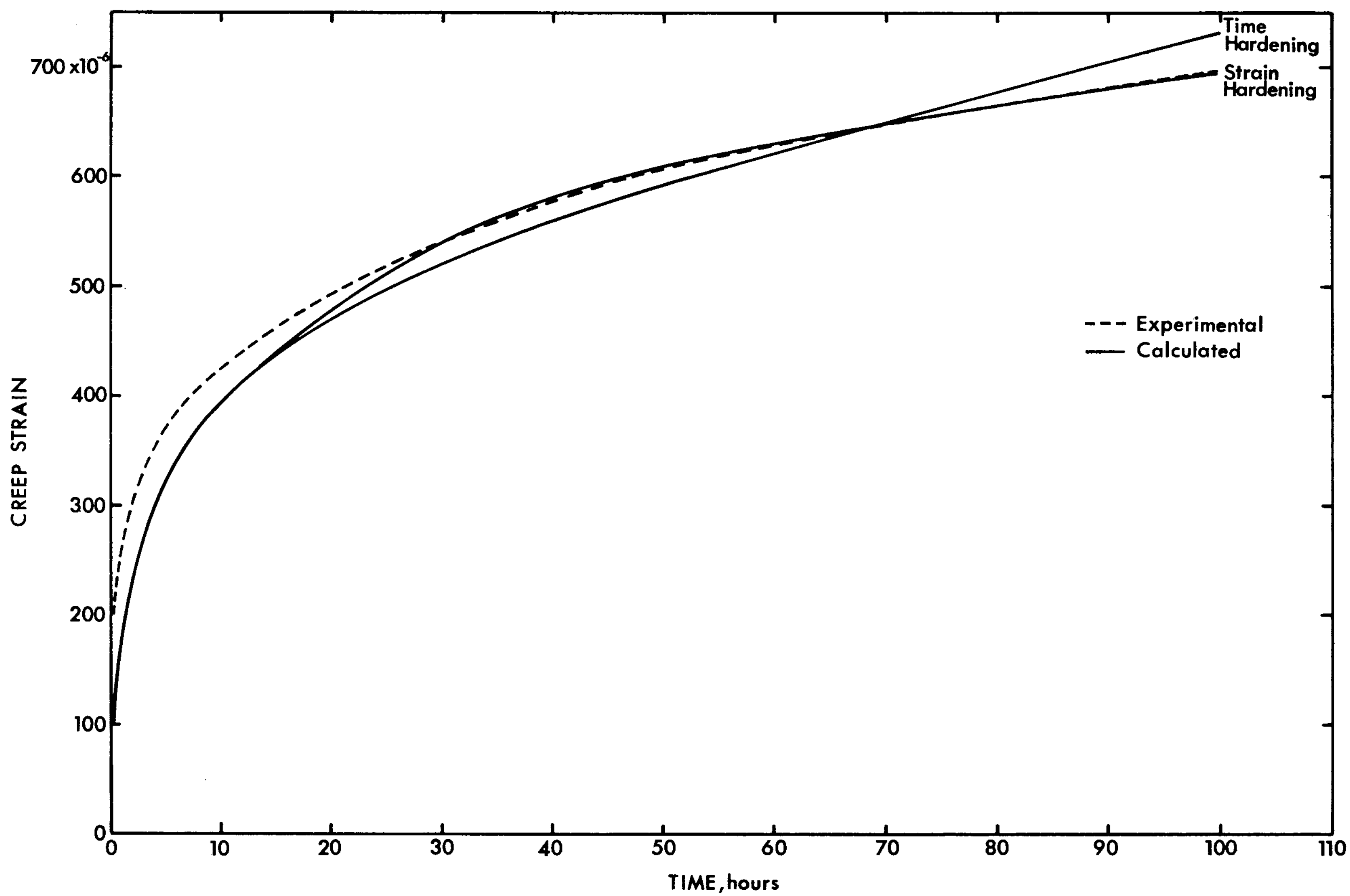

FIGURE 23 - Experimental and calculated creep curves for Specimen BA-29 (T=225 °F, 107 °C).

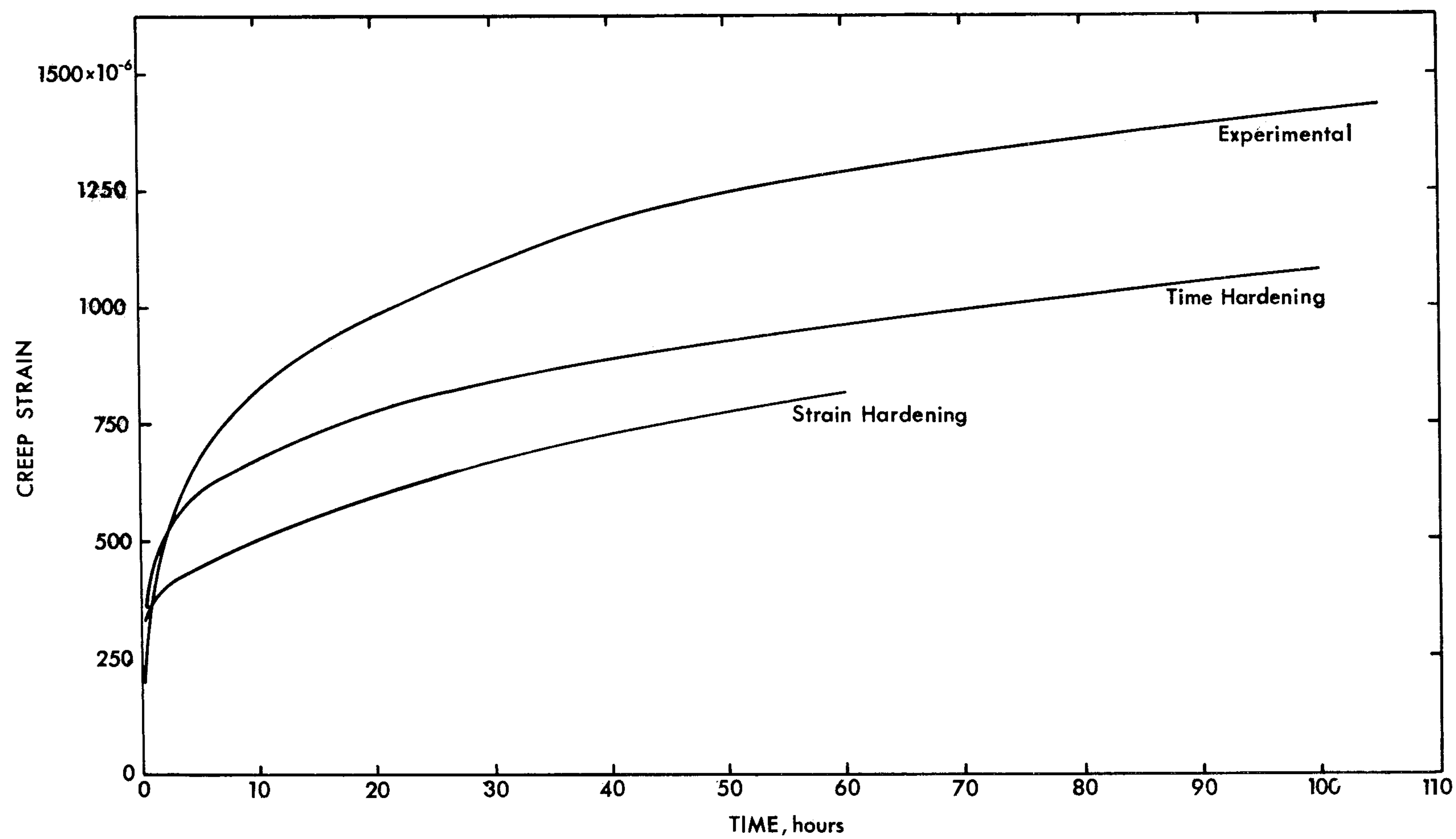

FIGURE 24 - Experimental and calculated creep curves for Specimen BA-16 (T = 225 °F, 107 °C).

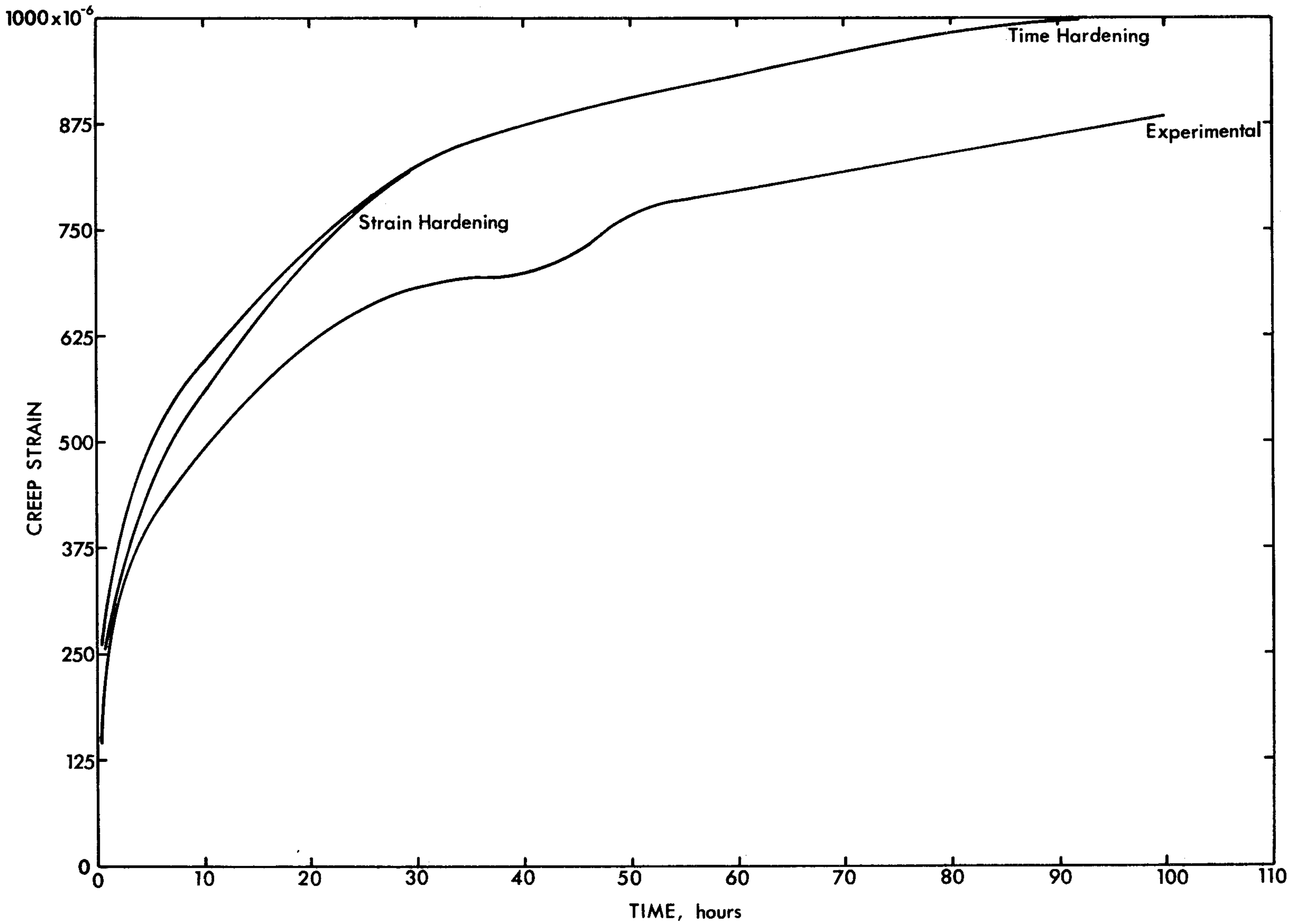

FIGURE 25 - Experimental and calculated creep curves for Specimen BA-19 (T = 300 °F, 149 °C).

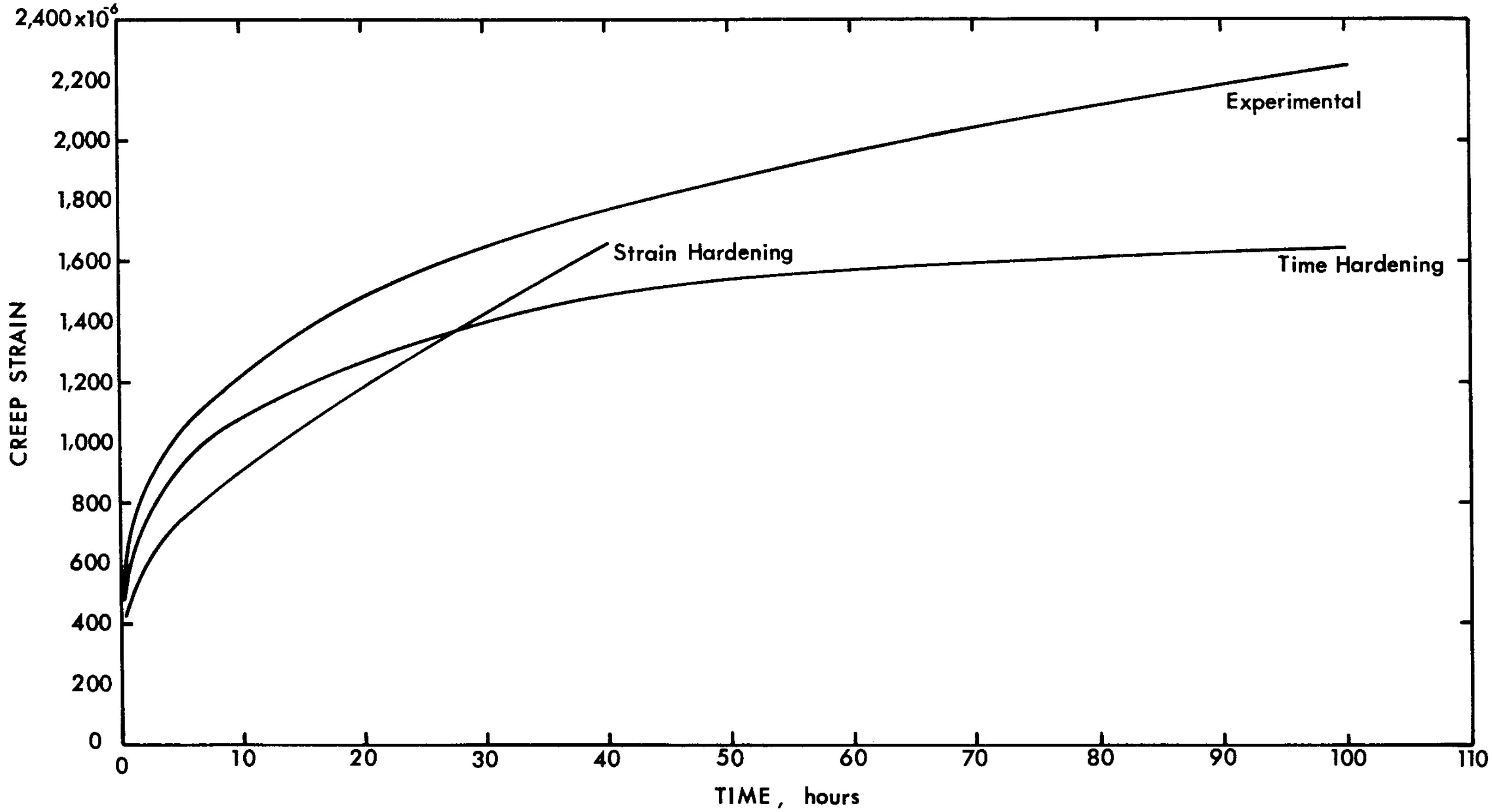

FIGURE 26 - Experimental and calculated creep curves for Specimen BA-31 (T = 300 °F, 149 °C).

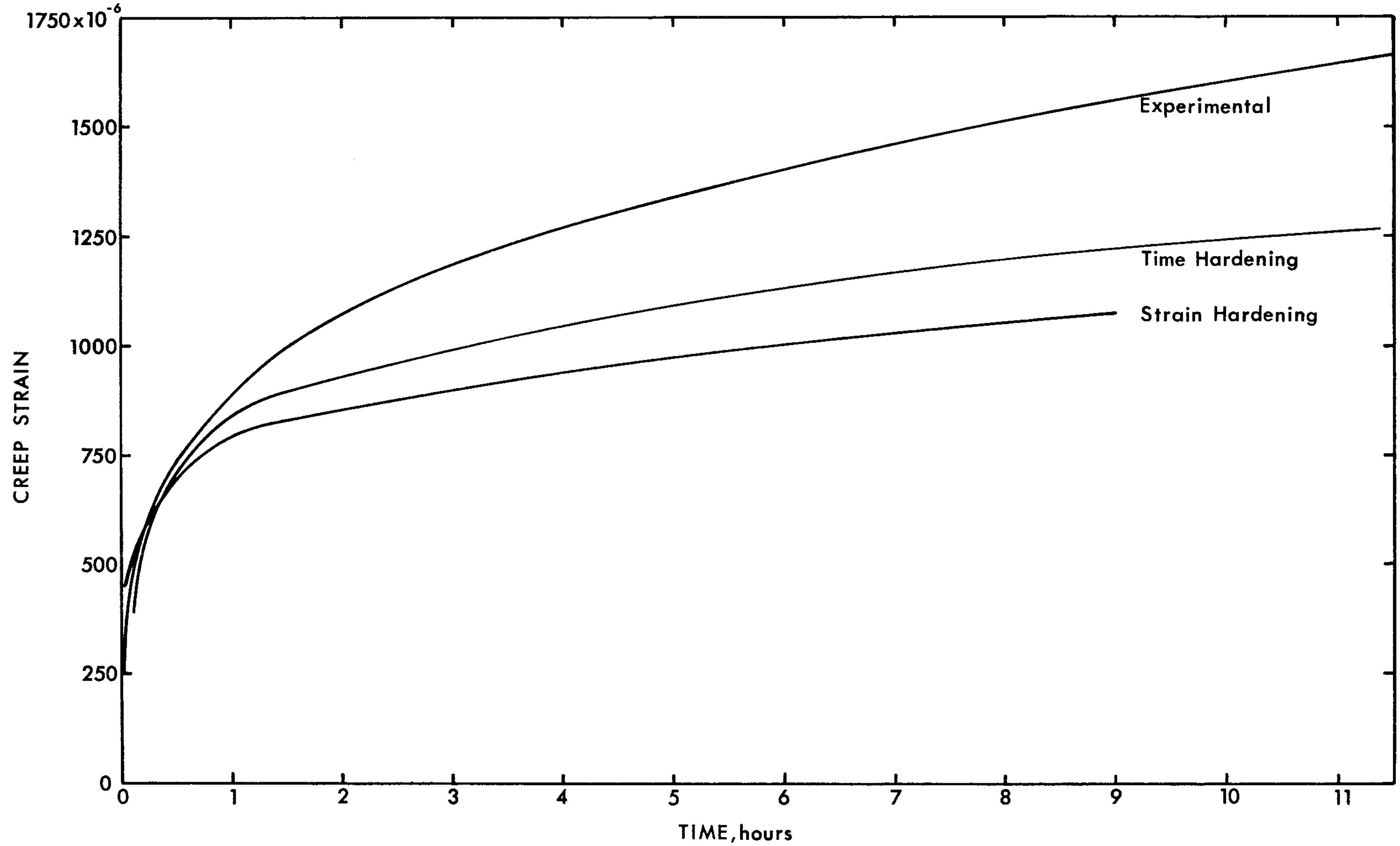

FIGURE 27 - Experimental and calculated creep curves for Specimen BA-20 (T = 300 °F, 149 °C).

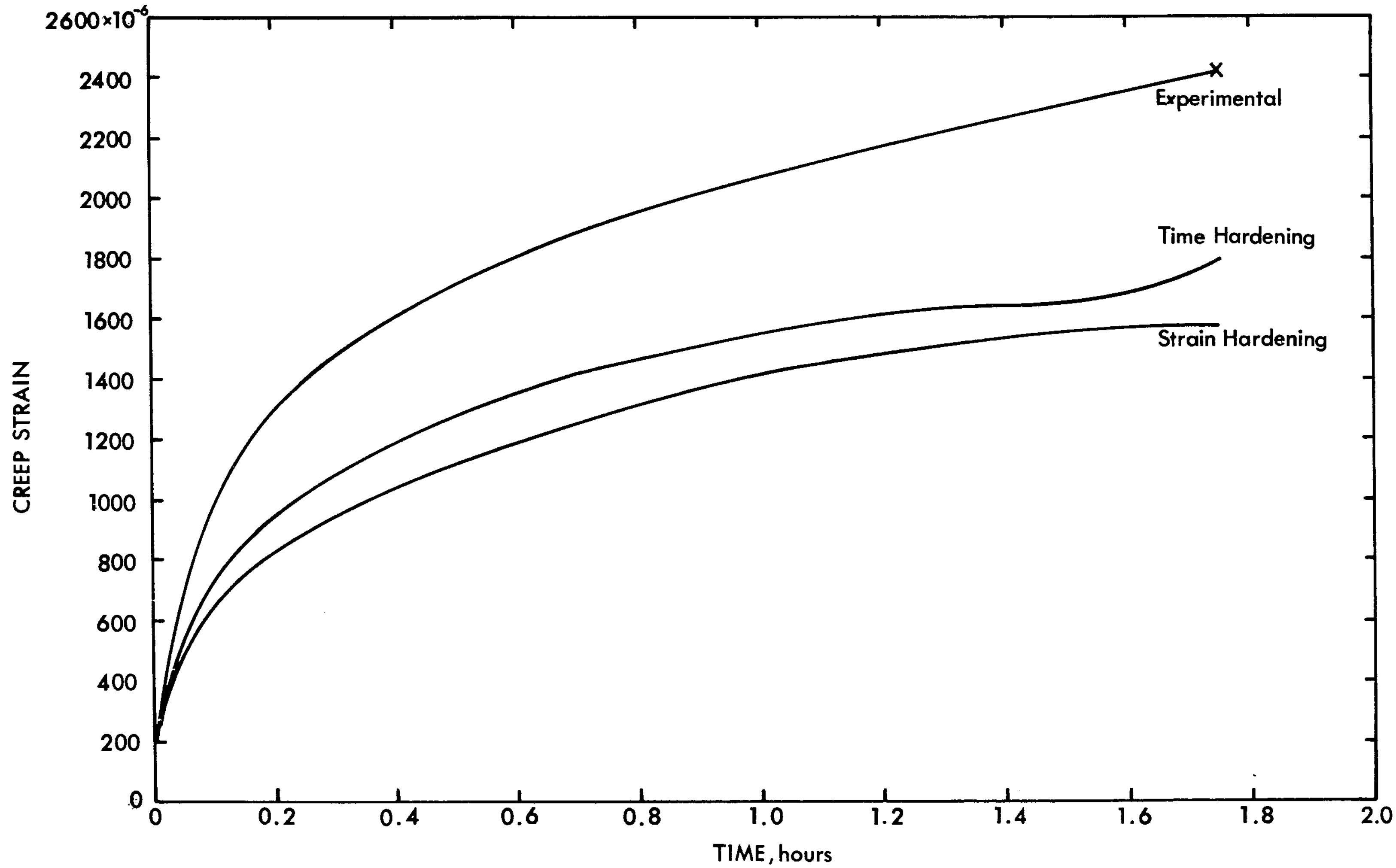

FIGURE 28 - Experimental and calculated creep curves for Specimen BA-25 (T = 300 °F, 149 °C).

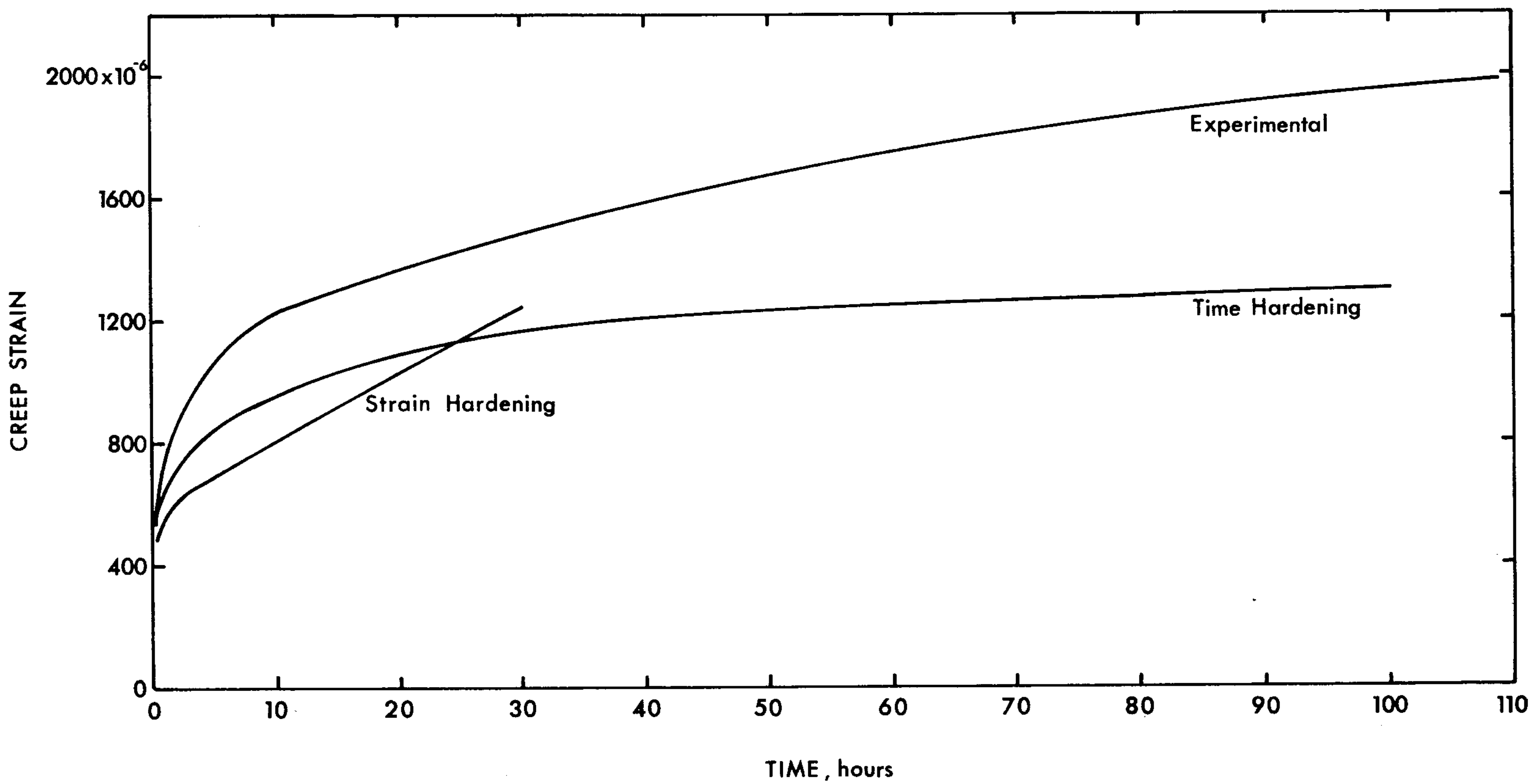

FIGURE 29 - Experimental and calculated creep curves for Specimen BA-27 (T = 300 °F, 149 °C).

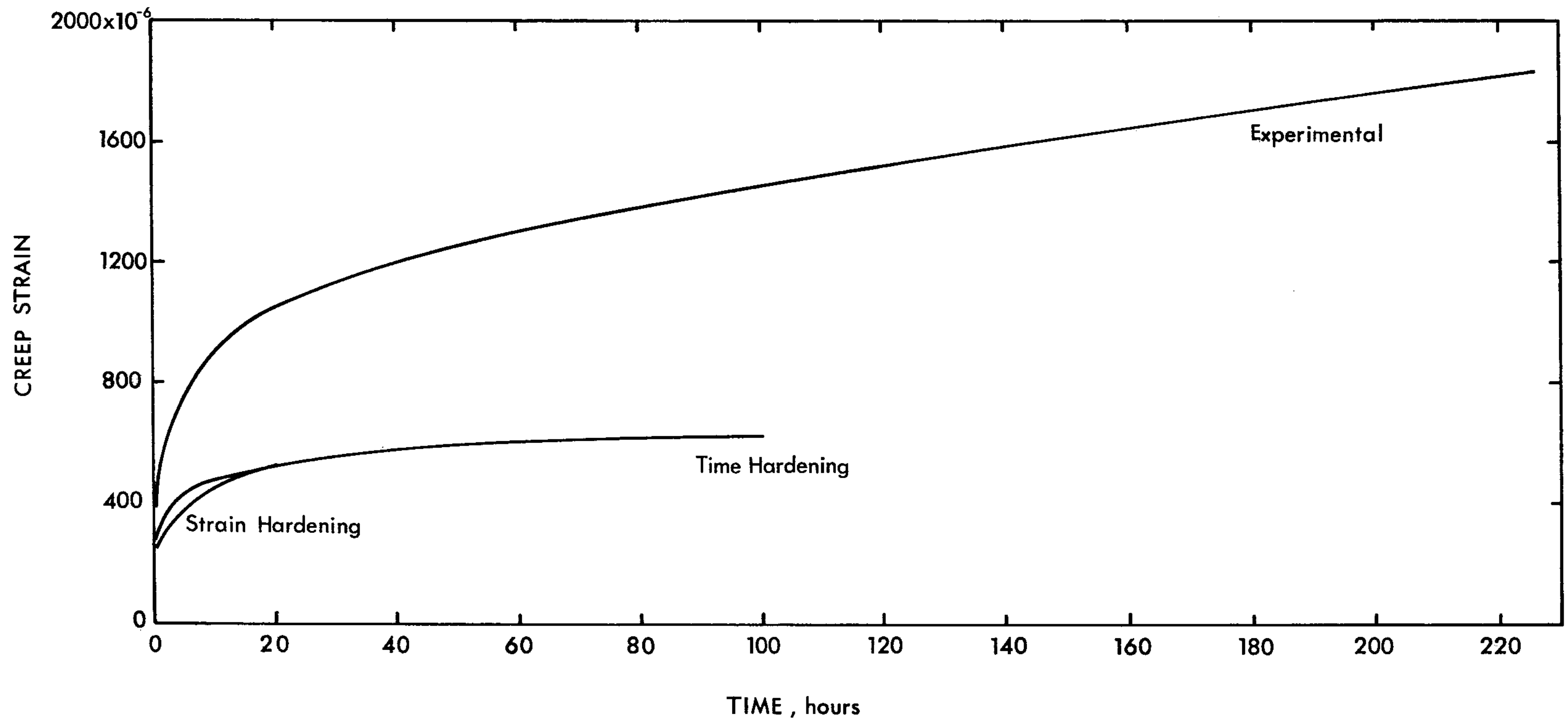

FIGURE 30 - Experimental and calculated creep curves for Specimen BA-39 (T = 300 °F, 149 °C).

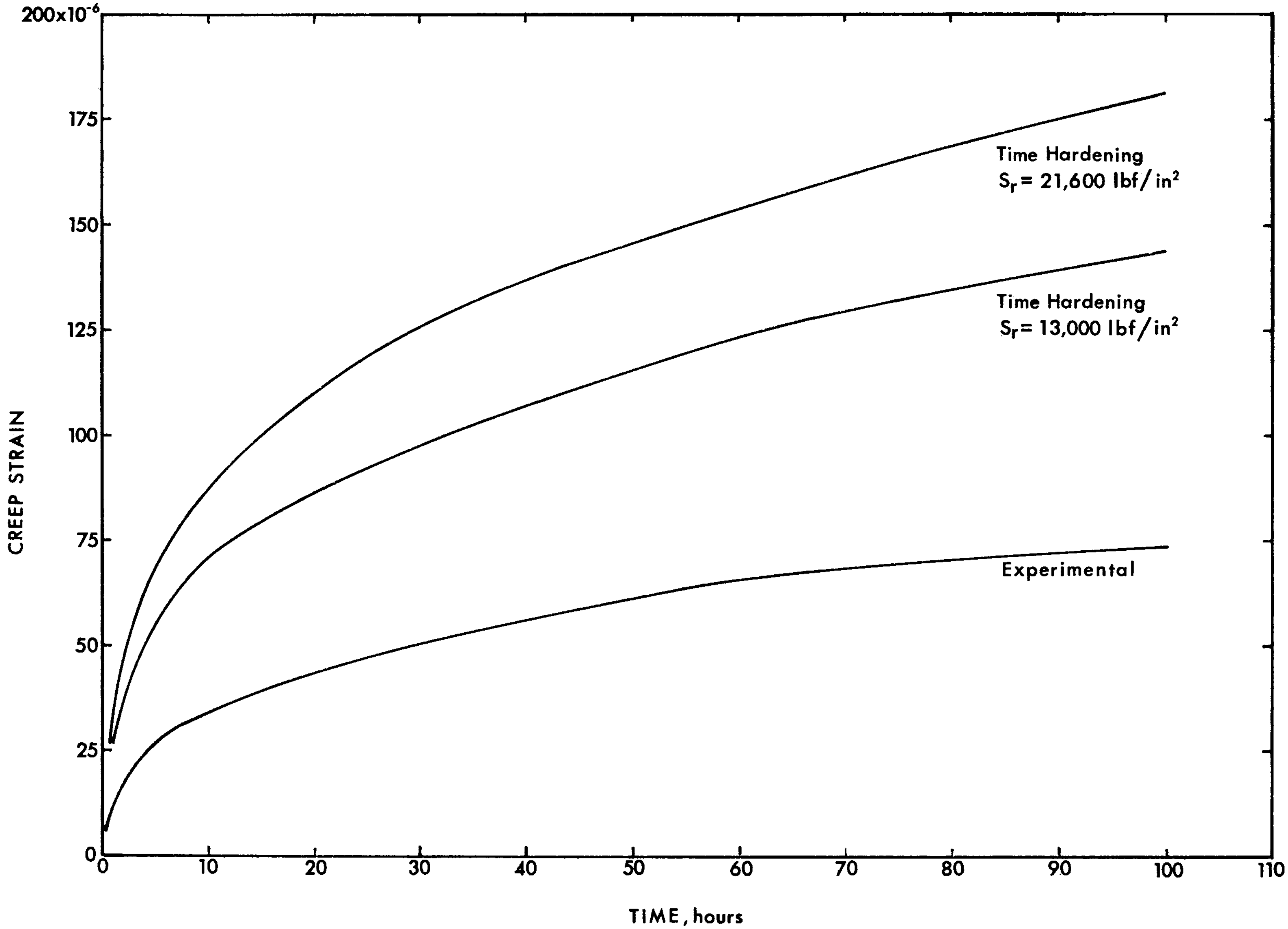

FIGURE 31 - Effect of residual stress on the calculated creep curve for Specimen BA-23 (T = 75 °F, 24 °C).

APPENDIX A

Conversion of U. S. Customary Units to SI Units

For simplicity, only U. S. customary units have been used in the tables and figures of this report. It should be noted that the U.S.A. is a signatory to the General Conference of Weights and Measures which gave official status to the metric SI system of units in 1960. Conversion factors for units used in this paper are given in the following table:

Physical quantity	U. S. customary unit	SI unit	Conversion factor
Force	pound-force (lbf)	newton (N)	1 lbf = 4.448 N
Length	inch (in)	meter (m)	1 in = 0.0254 m
Area	in^2	m^2	1 in^2 = 6.4516×10^{-4} m^2
Stress	lbf/in^2	N/m^2	1 lbf/in^2 = 6895 N/m^2
Temperature	°F	°C	°C = 0.556 (°F - 32)

Other conversion factors can be found in ASTM Standard Metric Practice Guide, ASTM Designation E380-70 (available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103).

APPENDIX B

Glossary

boron/epoxy - a composite consisting of continuous boron filaments in an epoxy matrix.

co-curing process - a process for fabricating sandwich specimens by which the boron/epoxy is cured and bonded to the metal in one operation.

composite - a material in which continuous high strength or high modulus fibers are deliberately oriented in a matrix in such a way as to increase its structural efficiency.

elastic follow-up technique - a technique for calculating creep strains of non-uniform structures which assumes that all load redistributions between components are elastic.

prepreg - pre-engineered, ready-to-mold combination of resin and reinforcement.

sandwich - a specimen consisting of a sheet of 7075-T6 aluminum alloy on each side of a boron/epoxy laminate.

strain-hardening rule - a theory of cumulative creep deformation which assumes that instantaneous creep rate is a function of stress and previous creep strain.

time-hardening rule - a theory of cumulative creep deformation which assumes that instantaneous creep rate is a function of stress and the time the material has been creeping.

two-step process - a process for fabricating sandwich specimens by which the boron/epoxy is first cured then bonded to the metal in a second operation.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Tensile creep tests were performed on twelve specimens of 0° unidirectional boron/epoxy and on twenty-four specimens of 7075-T6 aluminum alloy reinforced with 0° unidirectional boron/epoxy. An analytical procedure for predicting the creep properties of composite-reinforced metals is presented. Agreement between calculated and experimental creep curves varies with test temperature. These discrepancies between experiment and analysis are probably not due to an error in the analysis itself, but rather to uncertainty in the residual stresses in the specimens.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Aluminum alloy; boron/epoxy; composite materials; creep; elastic follow-up technique; sandwich specimen.

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